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# ADVANCES IN AGRONOMY

## VOLUME III

# ADVANCES IN
# AGRONOMY

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## VOLUME III

Edited by A. G. NORMAN
*Camp Detrick, Frederick, Maryland*

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## CONTRIBUTORS TO VOLUME III

G. W. BURTON, *Principal Geneticist, U. S. Department of Agriculture, Georgia Coastal Plain Experiment Station, Tifton, Georgia.*

H. J. HARPER, *Professor of Soils, Oklahoma Agricultural and Mechanical College, Stillwater, Oklahoma.*

J. A. MCMILLAN, *Ministry of Agriculture and Fisheries, London, England.*

R. Q. PARKS, *Assistant Head, Division of Soil Management and Irrigation, U. S. Department of Agriculture, Beltsville, Maryland.*

R. F. REITEMEIER, *Senior Soil Scientist, Division of Soil Management and Irrigation, U. S. Department of Agriculture, Beltsville, Maryland.*

R. W. SIMONSON, *Assistant Chief, Division of Soil Survey, U. S. Department of Agriculture, Beltsville, Maryland.*

A. L. TAYLOR, *Nematologist, U. S. Department of Agriculture, Beltsville, Maryland.*

C. J. WILLARD, *Professor of Agronomy, The Ohio State University, Columbus, Ohio.*

E. WINTERS, *Head, Department of Agronomy, University of Tennessee, Knoxville, Tennessee.*

# Preface

Although it is customary that there should be a preface to a volume of this nature, a preface is only justifiable if the Editor has some general remarks to make that do not lend themselves to inclusion elsewhere. He may set the stage, define the audience, outline the entertainment to be provided, or attempt to forestall the comments of the critics.

The Preface to Volume I followed this conventional form. It was stated therein that the newer developments in agronomy are so diverse and involve so many skills and disciplines that few can keep well informed. The topics to be reviewed would be those that might be expected to be of interest and assistance to agronomists in general, even if sometimes they went beyond the ill-defined boundaries of agronomy. Soil-plant relationships were to form the recurrent theme.

In this, Volume III, there has been no change in the general objectives. However, the article by McMillan, discussing the agronomic changes brought about in England and Wales under the stresses of the last decade, marks a new departure. This will be followed in later issues by similar papers reviewing agronomic trends elsewhere. In these, it is not the intent to deal primarily with production programs or land-use plans, although their implementation and impact on practice may well be relevant.

The contributors to this and previous volumes deserve recognition for their willingness to participate in the launching of a new venture, and for their accomplishments in setting high standards for others to follow.

A. G. NORMAN

*Frederick, Md.*
*September, 1951.*

# CONTENTS

Page

Contributors to Volume III . . . . . . . . . . . . . . . . . . . . v

Preface . . . . . . . . . . . . . . . . . . . . . . . . . vii

## The Subsoil

By E. Winters, *University of Tennessee, Knoxville, Tennessee,* and R. W. Simonson, *U. S. Department of Agriculture, Beltsville, Maryland*

I. Introduction . . . . . . . . . . . . . . . . . . . . . . 2

II. Concept of Subsoil . . . . . . . . . . . . . . . . . . . 4

III. Nature and Properties of Subsoil Layers . . . . . . . . . . . . 5

IV. Relationship of Subsoil to Plant Growth . . . . . . . . . . . 53

V. Management of Unexposed Subsoil . . . . . . . . . . . . . . 74

References . . . . . . . . . . . . . . . . . . . . . . . 86

## The Management of Alfalfa Meadows

By C. J. Willard, *The Ohio State University, Columbus, Ohio*

I. Introduction . . . . . . . . . . . . . . . . . . . . . . 94

II. The Effect of Cutting Systems on Amount and Quality of Hay . . . 94

III. The Effect of Different Systems of Cutting on Root Reserves . . . . 97

IV. The Relation of Various Factors to the Time of Cutting . . . . . . 102

V. Summary of Practical Recommendations for Cutting . . . . . . . . 107

VI. Cultivation of Established Alfalfa . . . . . . . . . . . . . . 108

VII. Other Weed Control Methods in Alfalfa . . . . . . . . . . . . 109

References . . . . . . . . . . . . . . . . . . . . . . . 110

## The Chemistry of Soil Potassium

By R. F. Reitemeier, *U. S. Department of Agriculture, Beltsville, Maryland*

I. Introduction . . . . . . . . . . . . . . . . . . . . . . 113

II. Forms of Soil Potassium and their Availability to Plants . . . . . . 114

III. Influences of other Cations on Forms of Soil Potassium . . . . . . 143

IV. Relationships of Soil Microorganisms to Soil Potassium . . . . . . 153

V. Effect of Aeration and Compaction on Availability of Potassium . . . 155

VI. Movement and Distribution of Potassium in the Soil Profile . . . . . 156

VII. Epilogue . . . . . . . . . . . . . . . . . . . . . . . 159

References . . . . . . . . . . . . . . . . . . . . . . . 159

## The Changing Pattern of Agriculture in England and Wales

By J. A. McMillan, *Ministry of Agriculture and Fisheries, London*

I. The Period 1921-1938 . . . . . . . . . . . . . . . . . . 165

II. The Period 1939-1945 . . . . . . . . . . . . . . . . . . 176

Page
III. The Period 1946-1950 . . . . . . . . . . . . . . . . . . . 186
IV. Future Trends . . . . . . . . . . . . . . . . . . . . . 192

### The Adaptability and Breeding of Suitable Grasses for the Southeastern States

By Glenn W. Burton, *U. S. Department of Agriculture, Georgia Coastal Plain Station, Tifton, Georgia*

I. Introduction . . . . . . . . . . . . . . . . . . . . . . 197
II. The Problem of Evaluating Grasses . . . . . . . . . . . . . 201
III. The Grasses . . . . . . . . . . . . . . . . . . . . . . 205
References . . . . . . . . . . . . . . . . . . . . . . 240

### Chemical Treatment of the Soil for Nematode Control

By A. L. Taylor, *U. S. Department of Agriculture, Beltsville, Maryland*

I. Introduction . . . . . . . . . . . . . . . . . . . . . . 243
II. The Practice of Soil Fumigation . . . . . . . . . . . . . 248
III. The Effects of Soil Fumigation . . . . . . . . . . . . . 256
IV. Summary . . . . . . . . . . . . . . . . . . . . . . . 261
References . . . . . . . . . . . . . . . . . . . . . . 263

### Problems and Progress of Soil Conservation in the United States

By H. J. Harper, *Oklahoma A. & M. College, Stillwater, Oklahoma*

I. Introduction . . . . . . . . . . . . . . . . . . . . . . 265
II. Educational and Financial Incentives for Soil Conservation . . . . . 267
III. Research for Soil and Water Conservation . . . . . . . . . . . 273
IV. Summary . . . . . . . . . . . . . . . . . . . . . . . 311
References . . . . . . . . . . . . . . . . . . . . . . 319

### Irrigation, Agriculture and Soil Research in the United States

By R. O. Parks, *Division of Soil Management and Irrigation, U. S. Department of Agriculture, Beltsville, Maryland*

I. Introduction . . . . . . . . . . . . . . . . . . . . . . 323
II. Historical Developments . . . . . . . . . . . . . . . . . 325
III. The Modern Period . . . . . . . . . . . . . . . . . . . 329
IV. The Future . . . . . . . . . . . . . . . . . . . . . . 342
References . . . . . . . . . . . . . . . . . . . . . . 344

Author Index . . . . . . . . . . . . . . . . . . . . . . . 345
Subject Index . . . . . . . . . . . . . . . . . . . . . . . 356

# The Subsoil

ERIC WINTERS AND ROY W. SIMONSON
*University of Tennessee, Knoxville, Tennessee, and U. S. Department of Agriculture, Beltsville, Maryland*

## CONTENTS

*Page*
I. Introduction . . . . . 2
II. Concept of Subsoil . . . . . 4
III. Nature and Properties of Subsoil Layers . . . . . 5
  1. B horizons . . . . . 6
    a. B Horizons of Podzolic Soils . . . . . 6
      (1) Physical Properties . . . . . 10
      (2) Clay Minerals . . . . . 12
      (3) Fertility Levels . . . . . 13
    b. B Horizons of Latosolic Soils . . . . . 15
      (1) Physical Properties . . . . . 17
      (2) Clay Minerals . . . . . 18
      (3) Fertility Levels . . . . . 19
    c. B Horizons of Chernozemic Soils . . . . . 21
      (1) Physical Properties . . . . . 23
      (2) Clay Minerals . . . . . 24
      (3) Fertility Levels . . . . . 25
    d. B Horizons of Desertic Soils . . . . . 27
      (1) Physical Properties . . . . . 28
      (2) Clay Minerals . . . . . 29
      (3) Fertility Levels . . . . . 29
  2. Pan Layers . . . . . 31
    a. Claypans . . . . . 31
      (1) Distribution . . . . . 31
      (2) Physical Properties . . . . . 33
      (3) Clay Minerals and Fertility Status . . . . . 34
    b. Fragipans . . . . . 36
      (1) Distribution . . . . . 36
      (2) General Characteristics . . . . . 37
    c. Hardpans . . . . . 39
      (1) Ortsteins . . . . . 39
      (2) Laterite Crusts . . . . . 40
      (3) Iron-Silica Hardpans of Dry Regions . . . . . 43
      (4) Caliche . . . . . 43
      (5) Other Hardpans . . . . . 45
  3. C and D Horizons . . . . . 46
    a. Depth to C and D Horizons . . . . . 46
    b. Ranges in Properties . . . . . 46
    c. Significance of Properties . . . . . 48
  4. Temperature Regimes . . . . . 48
  5. Variations in Nature and Properties . . . . . 51

Page
IV. Relationships of Subsoils to Plant Growth . . . . . . . . . . . . . 53
  1. Unexposed Subsoils . . . . . . . . . . . . . . . . . . . . 54
    a. Root Penetration . . . . . . . . . . . . . . . . . . 54
    b. Moisture Regimes . . . . . . . . . . . . . . . . . . 58
    c. Nutrient and Water Supplies . . . . . . . . . . . . . . 62
  2. Exposed Subsoils . . . . . . . . . . . . . . . . . . . . 64
    a. Physical Problems . . . . . . . . . . . . . . . . . . 67
      (1) B Horizons of Gray-Brown Podzolic Soils . . . . . 67
      (2) B Horizons of Prairie Soils . . . . . . . . . . . 68
      (3) B Horizons of Latosols . . . . . . . . . . . . . 69
      (4) Claypans . . . . . . . . . . . . . . . . . . . . 69
      (5) Laterite Crusts . . . . . . . . . . . . . . . . . 70
      (6) C and D Horizons . . . . . . . . . . . . . . . . 71
    b. Fertility Problems . . . . . . . . . . . . . . . . . 72
V. Management of Unexposed Subsoils . . . . . . . . . . . . . . 74
  1. Subsoil Compaction . . . . . . . . . . . . . . . . . . . 74
  2. Prevention and Correction of Subsoil Compaction . . . . . . . 76
    a. Deep Tillage . . . . . . . . . . . . . . . . . . . . 76
    b. Deep Rooting of Plants . . . . . . . . . . . . . . . . 78
  3. Liming and Fertilizing Subsoils . . . . . . . . . . . . . . 83
  4. Utilizing Subsoil Nutrients . . . . . . . . . . . . . . . 84
References . . . . . . . . . . . . . . . . . . . . . . . . . 86

## I. INTRODUCTION

In recent years, people using the soil have given more and more attention to what lies beneath the surface layer in trying to understand plant growth response and engineering performance. In the past, most people were concerned only with the surface layer although it was generally realized that subsoils were important in highway construction. Little importance was attached to the role of subsoil or subsurface layers in crop or forest production. Nowadays, growing recognition of the importance of subsoils to agriculture, forestry, and engineering is encouraging people to look for information on subsoil properties and behavior.

Subsoil layers are extremely important to crop production, pasture management, forest growth, soil conservation, and the construction of highways and airport runways. Strictly from an agricultural point of view, the subsoil deserves close attention because it affects soil management and crop production whether it underlies the normal surface layer or is exposed. Deeper layers of the soil have important effects on moisture regimes and aeration capacities; they may also supply certain plant nutrients. These soil conditions, in turn, affect the growth of crops, grasses, and trees. Furthermore, the fertility and permeability of the subsoil have direct bearing on erosion hazards when soils are used for production. Finally, subsoil materials are of prime importance in all highway and airport construction requiring cuts and fills. The importance to the engineer does not end with construction but continues with highway and runway maintenance, in which the relationships of subsoils to plant growth again become important.

Although the authors recognize the importance of subsoil to engineers, it is beyond the scope of this paper to discuss subsoil properties in relation to engineering. The discussion in this paper is therefore concerned with the properties and behavior of subsoils important chiefly to agriculture and forestry.

It should be recognized at the outset that precise data on subsoil properties are not plentiful. The considerable literature on profile characteristics of soils, especially the soils of humid-temperate regions, does provide some precise data on the physical and chemical properties of subsoils. Along with this literature on profiles, there is information on field characteristics of subsoils in soil survey publications. When all the information is considered collectively, however, the total is small as compared with that available for surface layers. Furthermore, much of the information available on subsoil properties is difficult to interpret in terms of plant growth.

The properties and behavior of subsoils are discussed on the basis of soil groups in order to simplify presentation and indicate more general relationships. The soil groups used in the presentation follow as closely as possible the suggestions offered in a symposium published in *Soil Science*, February, 1949. Further information on soil classification and geography is available in the U.S. Department of Agriculture Yearbook of Agriculture, *Soils and Men*, 1938, which includes a soil association map of the country. Additional information, especially on distribution of parent materials, is given in the *Atlas of American Agriculture*, 1935. The classification of soils into groups having similar properties has developed rapidly in recent years. Interested readers should consult the references cited for more information. Readers are also referred to the glossary in the 1938 Yearbook of Agriculture for definitions of technical terms in most instances. Only a few terms of special importance to the discussion are defined as they are introduced in this paper.

Because precise data on subsoil properties and behavior are commonly lacking, it is necessary in discussing subsoils to extrapolate from available information about representatives of great soil groups. For this reason, the review offered here differs somewhat from the reviews possible when much specific information on a given subject is at hand. In this paper, the approach followed has been one of summarization of available information on the kinds, characteristics, and behavior of subsoils by soil groups; evaluation of the various properties in terms of plant growth in so far as possible under existing limitations; and the outlining of more obvious deficiencies in our present knowledge.

## II. CONCEPT OF SUBSOIL

The term "subsoil" has been used in a number of different ways. The subsoil has been considered that part of the soil in which plant roots grow below the surface layer. Some use the term "subsoil" to refer to the B horizons of soils and the term "substratum" to refer to layers below the B horizon. The term "subsurface" usually refers to portions of the A horizon below the plow layer.

In this paper, the term "subsoil" will be used in a more inclusive sense and will refer to all horizons below the A in the soil profile (a vertical section to a depth of several feet). The horizons below A include B, C, and D, as well as various types of pans (layers) which are not usually given letter designations. The lower part of the A horizon will not be considered subsoil but will be referred to as a subsurface layer. Because the total thickness of the A horizon exceeds 15 to 18 in. in some soils, the subsurface layer thickness may be of considerable magnitude.

The nomenclature of soil horizons has been outlined recently in a revision of the Soil Survey Manual by the Soil Survey Staff (1951). Definitions of soil horizons given in that manual will be followed as closely as possible. Briefly, the A horizon is defined as a mineral layer of maximum organic matter accumulation and/or as the surface layer that is lighter in color than the underlying horizon and has lost some of its clay and sesquioxides. The B horizon is defined as the soil layer that contains an accumulation of clay and sesquioxides with small amounts of organic material and/or has a blocky or prismatic structure and a stronger color than the overlying or A horizon. The C horizon is the layer of unconsolidated material of similar composition underlying the B (or A) horizon and presumably the kind of material from which the overlying A and B horizons developed. The D horizon is any unconformable stratum below the C, or if the C is absent, below the B horizon. The D horizon may be consolidated or not. Consolidated D layers (bedrock) will not be discussed here. Unconsolidated, unconformable layers designated as D horizons replace C horizons in many soils and may have marked influence on plant growth. This is true, for example, when a D horizon of porous gravel underlies a shallow solum formed in silty loess.

The nomenclature and letter designations of pan layers in soils are still in question, largely because there has not been wide agreement about their origin and classification. Some pans are clearly B horizons, others lie within the C horizon, and some seem to be unconformable layers not necessarily related to the present soil profile. In this paper, pans are discussed under three general headings: viz., claypans, fragipans, and hardpans. The claypans, as the name implies, are subsoil layers very high in clay, strongly plastic, and slowly pervious to water and plant roots. Fragipan layers include those that are not definitely cemented but do have a high degree of compaction and low permeability (Soil Survey Staff, 1951). Fragipans usually are deeper in the profile than claypans, though this is not always true. Hardpans are indurated soil horizons and layers cemented by iron oxides, silica, organic matter, calcium carbonate, or combinations of two or more of those substances. Hardpans are commonly impervious. The various types of pans are discussed separately in later sections of the paper because of the marked influence they may have on the possible utilization of soils.

## III. Nature and Properties of Subsoil Layers

Major physical and chemical properties of various kinds of subsoil layers will be summarized in this section. For convenience in discussion, subsoil layers will be grouped into three major categories: B horizons, C and D horizons, and pan layers. When the B, C, and D horizons, as well as pan layers, are considered parts of the subsoil, it is apparent at once that there are differences within the subsoil itself. These differences may be either large or small. It is also apparent that there are differences between the subsoil layers on the one hand and the A horizon or surface soil on the other. Again the differences may be slight or they may be marked. For example, soils formed from recent alluvial deposits are often uniform to depths of several feet (Holmes and Hearn, 1942). Similarly, soils on steep slopes and soils formed from highly resistant disintegrated rock materials commonly lack distinct horizons. On the other hand, soils formed from parent material greatly altered by weathering on a land surface unchanged for a long interval have well-defined morphologies in which the A and B horizons are clearly differentiated. In some of these soils, as for example the Putnam series formed from loess in north central Missouri, the A and B horizons are sharply differentiated (Whiteside, 1944). Differences within the subsoil itself are usually smaller than the differences between it and the surface soil.

As a general rule, the ranges in properties of subsoils are greater within a given area than are the ranges in surface soil properties. Taking extremes in characteristics, subsoils range in texture from gravel to heavy clay, in reaction from very acid to strongly alkaline, in fertility from very low to very high, and in structure and consistence from granular and friable to blocky, hard and plastic, or even cemented. All these properties are significant to plant growth, as is also the specific combination of these properties. Yet, it is not possible to consider all the individual combinations that do exist. Only a small number of reference points in the entire range of subsoil properties can be considered in this paper. The authors do wish to call attention to this fact, however, so that readers will have a better opportunity to interpret properly the information summarized and analyzed in subsequent discussions.

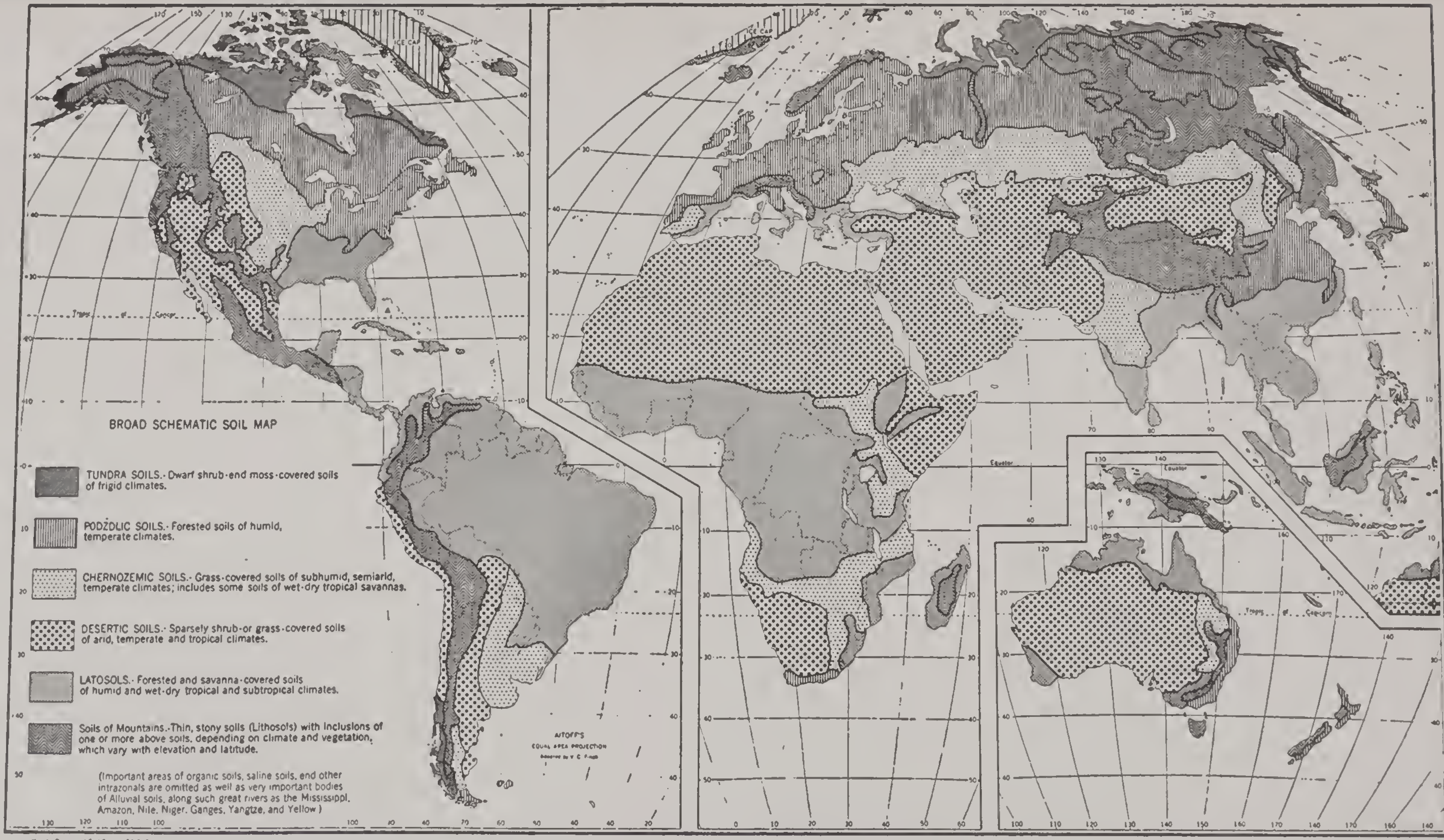
### *1. B Horizons*

The B horizon has previously been defined as that part of the soil between the A and C or D horizons. Lying as it does immediately beneath the A horizon or surface soil, the B horizon is more often important to plant growth than are other parts of the subsoil.

Because they are genetic soil layers, B horizons of well-drained soil types tend to be similar over broad geographic regions. The similarities exist especially in soils that are considered mature or zonal for a geographic region, i.e., those with well-developed morphology and fairly distinct A and B horizons. Because of similarities of this kind, soil types can be grouped in broad classes. Geographic zones dominated by these broad classes can then be shown on small-scale maps. In Fig. 1, a provisional schematic soil map of the world, six broad soil zones are shown (Orvedal, Kubota, and Smith, 1951). One of the zones shown on the map represents mountainous regions with large proportions of shallow soils and with complex local patterns of soil types. The other five zones are dominated by more restricted combinations of great soil groups.

Although B horizons with a number of properties in common can be recognized over broad regions, it is also important to recognize the ranges in properties that do exist. Considerable variations in B horizon properties occur in each of the soil regions shown in Fig. 1. Furthermore, wide variations may occur in adjacent soil types within a single field. These cannot be considered in this discussion of B horizons, which will be divided into four parts to apply to as many of the broad zones shown in Fig. 1.

*a. B Horizons of Podzolic Soils.* The podzolic soils have been formed under forest vegetation in humid, cool-temperate climates. The broad belts of podzolic soils are mainly in the northern hemisphere, as shown in Fig. 1. These broad zones include the regions of Podzols, Brown Podzolic, and Gray-Brown Podzolic soils of the northeastern United States shown in Fig. 2 (Kellogg, 1941). Regions of Brown Podzolic and Gray-Brown Podzolic soils in western Europe and the eastern United


BROAD SCHEMATIC SOIL MAP
TUNDRA SOILS.- Dwarf shrub-and moss-covered soils of frigid climates.
PODZOLIC SOILS.- Forested soils of humid, temperate climates.
CHERNOZEMIC SOILS.- Grass-covered soils of subhumid, semiarid, temperate climates; includes some soils of wet-dry tropical savannas.
DESERTIC SOILS.- Sparsely shrub-or grass-covered soils of arid, temperate and tropical climates.
LATOSOLS.- Forested and savanna-covered soils of humid and wet-dry tropical and subtropical climates.
Soils of Mountains.-Thin, stony soils (Lithosols) with inclusions of one or more above soils, depending on climate and vegetation, which vary with elevation and latitude.
(Important areas of organic soils, saline soils, and other intrazonals are omitted as well as very important bodies of Alluvial soils, along such great rivers as the Mississippi, Amazon, Nile, Niger, Ganges, Yangtze, and Yellow)
ICE CAP
ICE CAP
Tropic of Cancer
Equator
Equator
Tropic of Capricorn
AITOFF'S
EQUAL AREA PROJECTION

Map by Division of Soil Survey, BPISAE
U. S. Department of Agriculture July 1940

FIG. 1. Map showing soil zones of the world. The broad regions are characterized by generally similar processes of genesis reflected in the well-drained profiles with undulating to rolling topography. The mature soils of any one zone are similar in a number of important properties but differ in others. Many of the intrazonal and azonal soils cannot be indicated with the small scale.

States have been of special importance to western culture. The general characteristics of the soils are indicated in the podzolic profile diagram in Fig. 3,which illustrates major horizons to depths of 5 ft. (Orvedal, Kubota, and Smith, 1951). The podzolic profile diagram represents especially the group of Gray-Brown Podzolic soils. Cline (1949) has recently described the Podzol, Brown Podzolic, and Gray-Brown Podzolic soils of New York and discussed their interrelationships.

Soils of many other groups are associated with the podzolic soils. This is indicated to some degree by the areas of Bog and Humic-Gley (Wiesenboden) soils in the northeastern United States (Fig. 2). These two groups are but a small part of those associated with the zonal or mature soils in each region. The subsoils of these associated soils have some properties in common with the B horizons of podzolic soils in many instances.

In this discussion of podzolic soils mention should perhaps be made of the Tundra soils. Information on the soils of the tundra zone is meager, although they have been examined in Siberia by Nikiforoff (1928), in Canada by Leahey (1947), and in Alaska by Kellogg and Nygard (1951). On the basis of limited evidence, the horizons of many soils of the tundra zone seem to be similar to but thinner than those of the podzolic soils in more temperate zones. Available evidence suggests that the upper horizons are not distinct except in color. Feustel, Dutilly, and Anderson (1939) report low percentages of clay in Tundra soils from northern Canada. The clay minerals were mainly of the 2:1 lattice type with small quantities of the 1:1 lattice type. In this respect, Tundra soils resemble Brown Podzolic soils. On the other hand, the occurrence of permafrost beneath the Tundra profile introduces a unique "subsoil" property, the significance of which is but partially understood. The "ever-frozen subsoil" poses a number of problems in using soils for agriculture or engineering. Mention is made of the Tundra soils because of their large area, but the character and significance of the Tundra subsoils are not discussed, partly because of the restricted agricultural importance of the soils themselves and partly because of the limited information available.

The B horizons of mature podzolic soils generally are higher in free oxides, clay or both and have brighter colors than do the A and C horizons, ranging from yellow or yellowish brown through brown to yellowish red. They are commonly more blocky in structure, less friable in consistence, and lower in organic matter than the A horizons. For the most part, they differ in the same ways from the C horizons except that the latter are lower in organic matter and nitrogen. In some Podzols, the B horizon contains more organic matter than does the lower

GENERAL PATTERN OF GREAT SOIL GROUPS

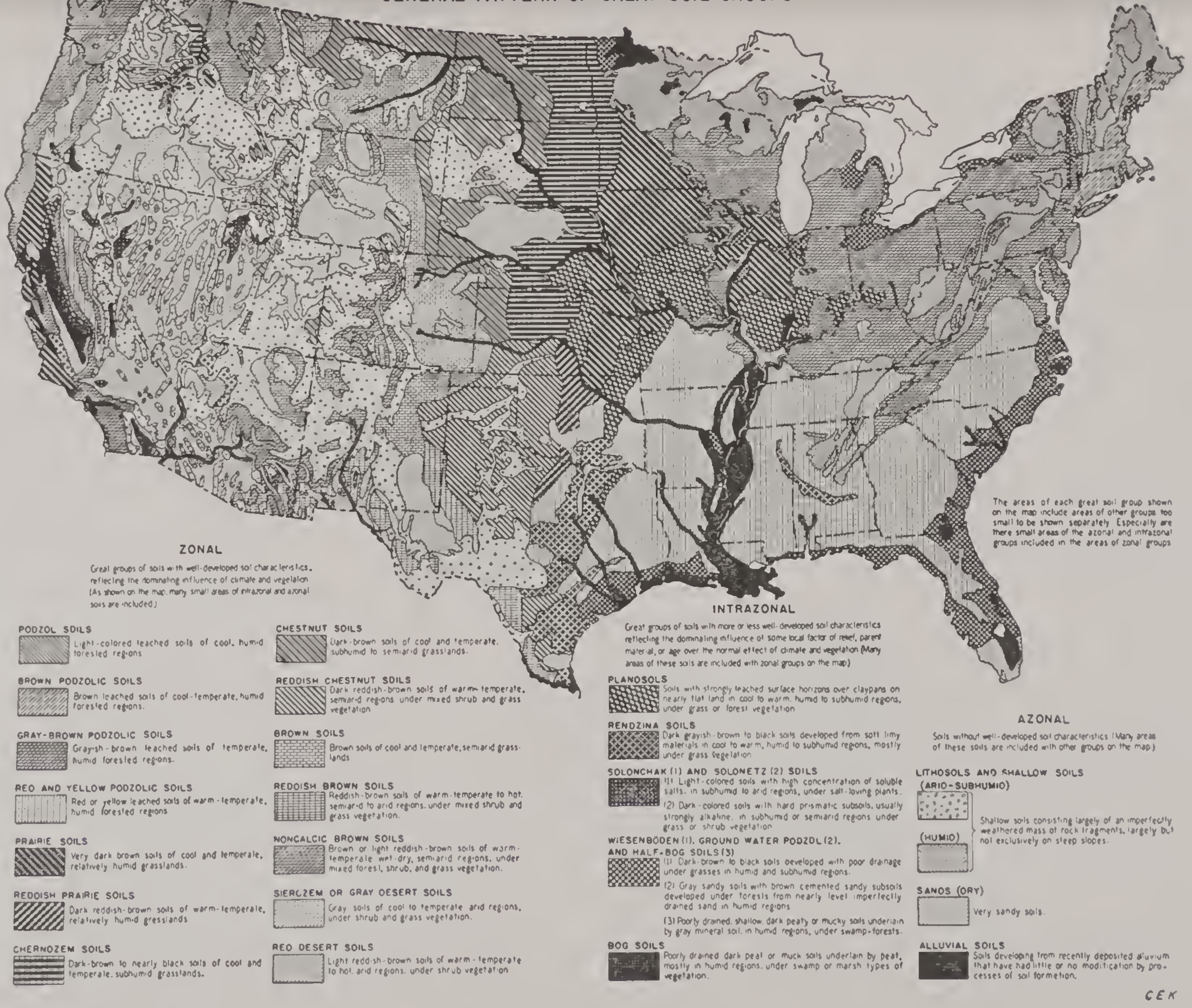

The areas of each great soil group shown on the map include areas of other groups too small to be shown separately. Especially are there small areas of the azonal and intrazonal groups included in the areas of zonal groups
ZONAL
Great groups of soils with well-developed soil characteristics, reflecting the dominating influence of climate and vegetation (As shown on the map, many small areas of intrazonal and azonal soils are included.)
PODZOL SOILS
Light-colored leached soils of cool, humid forested regions
BROWN PODZOLIC SOILS
Brown leached soils of cool-temperate, humid forested regions.
GRAY-BROWN PODZOLIC SOILS
Grayish-brown leached soils of temperate, humid forested regions.
RED AND YELLOW PODZOLIC SOILS
Red or yellow leached soils of warm-temperate, humid forested regions
PRAIRIE SOILS
Very dark brown soils of cool and temperate, relatively humid grasslands.
REDDISH PRAIRIE SOILS
Dark reddish-brown soils of warm-temperate, relatively humid gresslands
CHERNOZEM SOILS
Dark-brown to nearly black soils of cool and temperate, subhumid grasslands.
CHESTNUT SOILS
Dark-brown soils of cool and temperate, subhumid to semiarid grasslands.
REDDISH CHESTNUT SOILS
Dark reddish-brown soils of warm-temperate, semiarid regions under mixed shrub and grass vegetation
BROWN SOILS
Brown soils of cool and temperate, semiarid grasslands
REDDISH BROWN SOILS
Reddish-brown soils of warm-temperate to hot, semiarid to arid regions, under mixed shrub and grass vegetation.
NONCALCIC BROWN SOILS
Brown or light reddish-brown soils of warm-temperate wet-dry, semiarid regions, under mixed forest, shrub, and grass vegetation.
SIEROZEM OR GRAY DESERT SOILS
Gray soils of cool to temperate arid regions, under shrub and grass vegetation.
RED DESERT SOILS
Light reddish-brown soils of warm-temperate to hot, arid regions, under shrub vegetation
INTRAZONAL
Great groups of soils with more or less well-developed soil characteristics reflecting the dominating influence of some local factor of relief, parent material, or age over the normal effect of climate and vegetation (Many areas of these soils are included with zonal groups on the map)
PLANOSOLS
Soils with strongly leached surface horizons over claypans on nearly flat land in cool to warm, humid to subhumid regions, under grass or forest vegetation
RENDZINA SOILS
Dark grayish-brown to black soils developed from soft limy materials in cool to warm, humid to subhumid regions, mostly under grass vegetation
SOLONCHAK (1) AND SOLONETZ (2) SOILS
(1) Light-colored soils with high concentration of soluble salts, in subhumid to arid regions, under salt-loving plants.
(2) Dark-colored soils with hard prismatic subsoils, usually strongly alkaline, in subhumid or semiarid regions under grass or shrub vegetation
WIESENBÖDEN (1), GROUND WATER PODZOL (2), AND HALF-BOG SOILS (3)
(1) Dark-brown to black soils developed with poor drainage under grasses in humid and subhumid regions.
(2) Gray sandy soils with brown cemented sandy subsoils developed under forests from nearly level imperfectly drained sand in humid regions
(3) Poorly drained, shallow, dark peaty or mucky soils underlain by gray mineral soil, in humid regions, under swamp-forests.
BOG SOILS
Poorly drained dark peat or muck soils underlain by peat, mostly in humid regions, under swamp or marsh types of vegetation.
AZONAL
Soils without well-developed soil characteristics (Many areas of these soils are included with other groups on the map)
LITHOSOLS AND SHALLOW SOILS
(ARID-SUBHUMID)
(HUMID)
Shallow soils consisting largely of an imperfectly weathered mass of rock fragments, largely but not exclusively on steep slopes.
SANDS (DRY)
Very sandy soils.
ALLUVIAL SOILS
Soils developing from recently deposited alluvium that have had little or no modification by processes of soil formation.
CEK

FIG. 2. Map showing general pattern of great soil groups in the United States, with major or dominant groups represented. Each unit on the map is a broad soil association, the pattern of which includes a number of minor soils that cannot be indicated.

A horizon, whereas this reversal is not found in Brown Podzolic and Gray-Brown Podzolic soils. The thickness of B horizons in podzolic soils ranges from a few inches to several feet. A rough average figure for Podzols and Brown Podzolic soils would be slightly less than 1 ft., whereas for Gray-Brown Podzolic soils it is about 2 ft. Although B horizons of the podzolic soils tend to differ in the same ways from the A and C horizons in every profile, they cover a wide range in properties (Kellogg, 1930; Brown and Byers, 1938; Brown and Thorp, 1942).

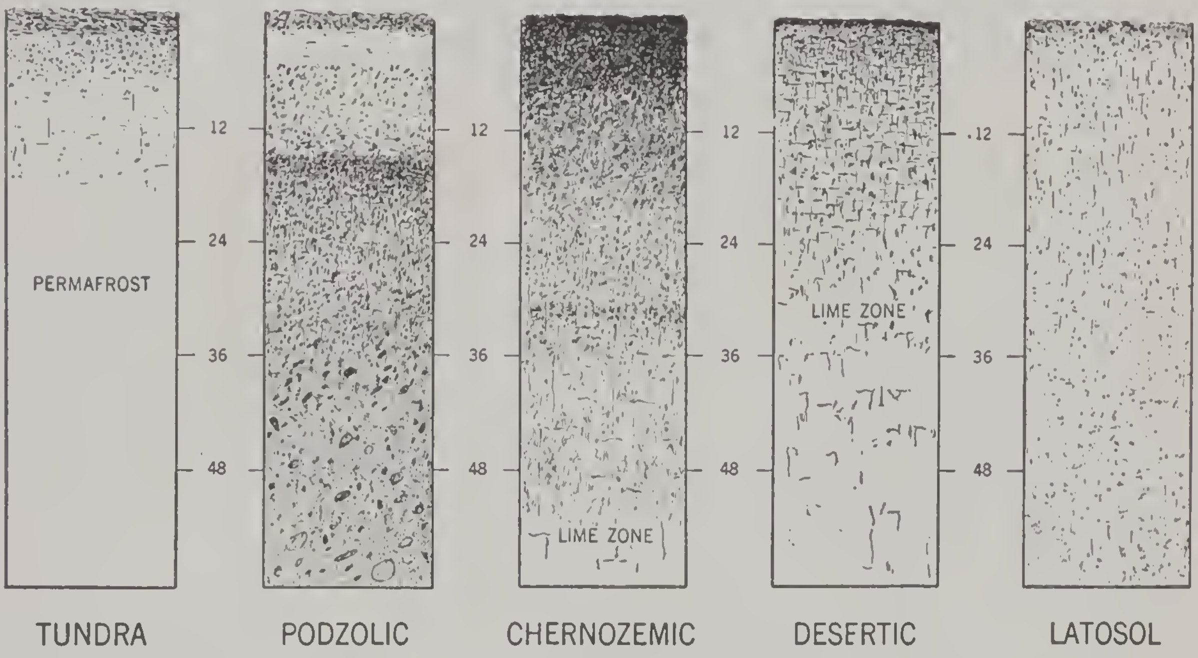


FIG. 3. Diagrams of representative profiles, somewhat idealized, of five suborders of zonal soils. The diagrams illustrate the degree of horizon differentiation and certain additional profile features of the major zonal great soil groups in the regions outlined on the map in Fig. 1. Profile depths are given in inches.

*(1) Physical properties.* The texture of podzolic B horizons ranges from loamy sands at the one extreme to clays at the other. On the whole, Podzols and Brown Podzolic soils have coarser-textured B horizons than Gray-Brown Podzolic soils. Common textures in those B horizons are sandy loams and loams (Lyford, 1946). In Gray-Brown Podzolic soils, the common textures of the B horizons are clay loams and silty clay loams (Kellogg, 1939; Brown and Thorp, 1942). Thus, in spite of the wide absolute range in textures in B horizons of podzolic soils, there is a strong tendency for intermediate textures to predominate.

The texture of the B horizon is affected much by the parent material from which the soil was formed. This influence is illustrated in the clay contents of B horizons in Miami silt loam and Hillsdale fine sandy loam (Brown and Thorp, 1942). Maximum clay contents in the B horizon are 37 per cent in Miami silt loam and 19 per cent in Hillsdale fine sandy loam. Ratios between the clay contents of the B and C horizons are essentially the same in the two soils. The relationship in texture between the B and C horizons is also indicated by profile data from Wisconsin (Kellogg, 1930). A similar relationship seems to exist in the Brown Podzolic soils in New England (Lyford, 1946; Lunt, 1948) in which the B and C horizons are commonly more sandy. These horizons are generally low in clay and relatively permeable.

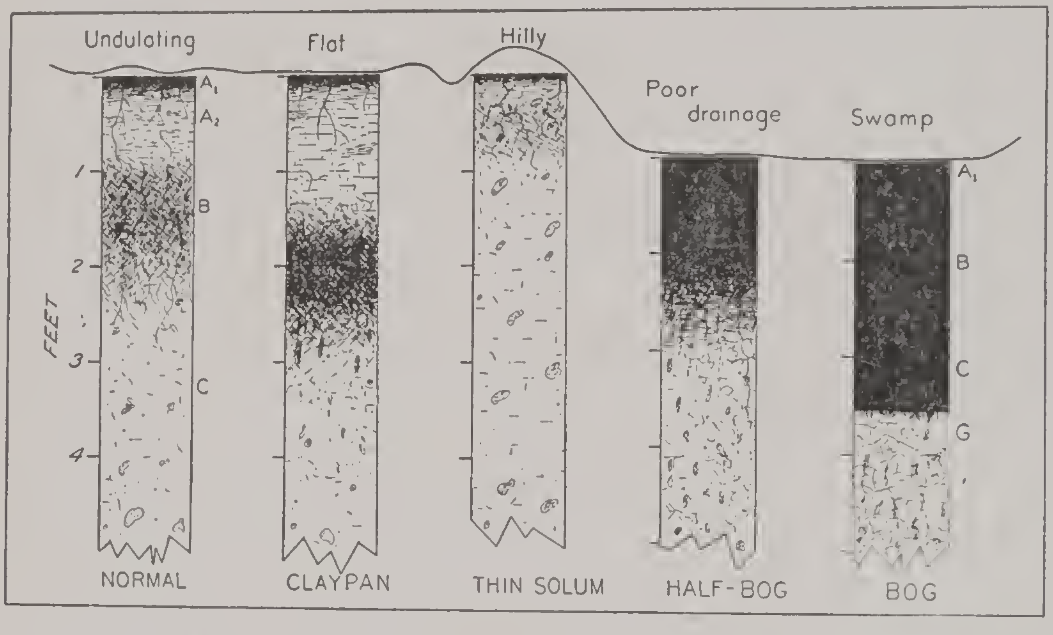


FIG. 4. Diagrams of soil profiles developed from similar parent materials but with differing topography in the region of Gray-Brown Podzolic soils shown in Fig. 2. The normal profile in this group is the zonal soil profile shown as the podzolic diagram in Fig. 3. It occupies the undulating topography, whereas the other profiles occupy flat, hilly, and depressed areas. On flat uplands where the water table is low, the soil has a highly leached A horizon and a distinct claypan, whereas in hilly areas the profile has a thin poorly developed solum because of excessive run-off and erosion. Organic matter accumulates as peat or muck in depressions. Examples from the detailed classification are the Miami, Crosby, Rodman, Brookston, and Carlisle series.

The B horizons of podzolic soils seem to be moderately permeable, on the whole. Those of Podzols and Brown Podzolic soils, more sandy as a rule, are also more permeable generally than the B horizons of Gray-Brown Podzolic soils. Although the more sandy B horizons are usually more permeable, the correlation is far from perfect. Occasional finer-textured B horizons have more root channels, worm holes, and structure cracks and are therefore more permeable than corresponding horizons lower in clay. As a rule, B horizons are less permeable than

A or C horizons. In Gray-Brown Podzolic profiles approaching Planosols in the character of B horizon, the B horizons are slowly permeable. Accurate published data on the permeability of podzolic B horizons are few, partly because of the difficulties in making reliable measurements.

*(2) Clay minerals.* Although the clay minerals in soils have been actively studied during recent years (Gieseking, 1949), there is much to be learned about the kinds and amounts in different soils. More data are available for the Gray-Brown Podzolic soils than for Podzols and Brown Podzolic soils. The dominant clay mineral seems to be of the 2 : 1 lattice type with illite more common than montmorillonite. Kaolinite (1 : 1 lattice type) and other minerals also occur in the clay fraction. Alexander, Hendricks, and Nelson (1939) identified illite as the dominant clay mineral in several soils representing the Gray-Brown Podzolic group. Further support of this identification is provided by the high contents of potassium in the colloid fraction from certain Gray-Brown Podzolic soils (Byers, Alexander, and Holmes, 1935). Russell and Haddock (1940) also found illite in a Gray-Brown Podzolic soil formed from loess in Iowa though as much montmorillonite was also present. Available data suggest that Gray-Brown Podzolic soils associated with Prairie soils are higher in montmorillonite and lower in illite than those farther east in the United States. Studies by Peterson (1946a) indicate that the kinds of clay minerals found in Gray-Brown Podzolic profiles are a function of parent materials as well as soil formation. Soils formed from parent materials high in kaolinite have that mineral as the dominant species in the clay fraction. All investigations thus far show few changes in kinds of clay minerals within a profile unless there is an unconformity in parent material.

Not many efforts have been made to identify clay mineral species in Podzols and Brown Podzolic soils. Richard and Chandler (1943) report illite (2 : 1) as dominant and kaolinite (1 : 1) as a minor clay mineral in Podzols from Quebec. Haddock (1943) considered illite the most important clay mineral in several Brown Podzolic soils in New England. The moderate to high contents of potassium in the colloidal fractions of Caribou loam (Byers, Alexander, and Holmes, 1935) and Gloucester sandy loam (Brown and Byers, 1938) also suggest the presence of appreciable quantities of illite. Apparently noncrystalline substances are common in the clay fractions of Podzols and are present but less important in Brown Podzolic soils. Richard and Chandler (1943) extracted large quantities of free oxides from the B horizons of Podzols from Quebec. In a study of certain soils in Scotland, Mackenzie (1949) reports 31 per cent of the clay fraction from one of the deeper horizons as free oxides which resemble "cold-precipitated" hydrated ferric oxide. Walker (1950) has also reported that amorphous iron and aluminum oxides are widespread in soil clays of northeast Scotland. It may be that similar free oxides occur widely in B horizons of Podzols and to a lesser extent in the B horizons of Brown Podzolic soils. Frei and Cline (1949) describe yellowish red coatings considered to be sesquioxides in the B horizons of Brown Podzolic soils.

Differences in clay mineral species in the various podzolic soils are responsible to a large extent for differences in plasticity and exchange capacities of B horizons. The hydrous oxides and kaolinite have low exchange capacities and plasticities, whereas illite and montmorillonite are medium to high. In Podzols, the base exchange capacity of the B horizon is much more dependent upon the content of organic matter than it is in Gray-Brown Podzolic and Brown Podzolic soils. For the podzolic soils as a whole, the exchange capacities are moderate to high on the basis of the amount of clay present. The B horizons with their higher contents of clay, dominantly of the 2:1 type, are more plastic and less friable than the A horizons. This becomes especially significant if the A horizon is removed by natural or artificial means and the B horizon must be cultivated.

*(3) Fertility levels.* The plant nutrient status or fertility levels of B horizons may be either higher or lower than those of the A and C horizons. In most cases, the total quantities of calcium, magnesium, and potassium are higher in the B and C horizons than in the A horizons (Marbut, 1935). Total quantities of phosphorus, however, are variable. Except for some of the Podzols, the total quantities of organic matter and nitrogen are highest in the A horizons. The total quantities of nutrient elements are not directly related to plant growth, but they do represent reservoirs for possible future use. As a rule, the amounts of plant nutrients in available forms are lower in the B horizons than in the A horizons of podzolic soils, but this general rule has its usual quota of exceptions.

Organic matter contents are commonly much lower in the B than in the A horizons of podzolic soils. Excluding Podzols for the moment, the contents of organic carbon in B horizons range below 0.5 per cent (Brown and Byers, 1938; Brown and Thorp, 1942). The contents of organic carbon in Podzol B horizons commonly range from 3 to 10 per cent (Brown and Byers, 1938; Richard and Chandler, 1943), whereas those of nitrogen are near 0.3 per cent (Edgington and Adams, 1925). With the prevailing low contents of organic matter, the amounts of phosphorus in organic form are also low. Pearson and Simonson (1939) found 8 and 45 p. p. m. of organic phosphorus in the B horizons of two Gray-

Brown Podzolic soils in Iowa. The two amounts reflect the fertility status and degree of weathering of the two soils. On the whole, podzolic B horizons are appreciably lower in organic matter, nitrogen, organic phosphorus, and sulfur than the A horizons. They are, however, higher in all these substances than the C horizons.

Total phosphorus may be as plentiful in podzolic B horizons as in the A horizons, but the latter are generally higher in available phosphorus (Lohse and Ruhnke, 1933; Marbut, 1935). Occasional exceptions have been observed. Pearson, Spry, and Pierre (1940) report large quantities of dilute-acid soluble phosphorus in the deeper B horizons of Gray-Brown Podzolic soils formed from loess in Iowa. A similar situation seems to exist in soils developed on deep loess east of the Mississippi River in Kentucky and Tennesee. The B horizon of Memphis silt loam near the river bluffs contains large amounts of available phosphorus. The Maury and related series formed from phosphatic rock in the Blue Grass regions of Kentucky and Tennessee are high in total and available phosphorus throughout the profile. Phosphatic parent materials also occur locally elsewhere, but their total acreage is fairly small. Podzolic B horizons are usually low in available phosphorus, commonly low in organic phosphorus, and medium in total phosphorus.

The status of exchangeable calcium, magnesium, and potassium in podzolic B horizons is complex. The B horizons of Gray-Podzolic soils such as Fayette silt loam contain more exchangeable calcium, magnesium, and potassium than the A horizons (Smith, Allaway, and Riecken, 1950). Quantities of exchangeable cations per 100 grams soil are 12 milliequivalents (me.) of calcium, 6 me. of magnesium, and 0.6 me. of potassium. These quantities represent the upper end of the range for exchangeable cations in B horizons of Gray-Brown Podzolic soils. The quantities commonly present are about half as large. The smallest amounts of exchangeable cations in B horizons of Gray-Brown Podzolic soils are from 5 to 10 per cent of the levels in Fayette silt loam. Base saturation usually falls between 40 and 60 per cent but may range from 30 to 80 per cent. The base status is lowest in B horizons of soils that have been strongly weathered and in soils that have been formed from strongly weathered parent materials. The highest levels of exchangeable cations occur in B horizons of soils from relatively young parent materials.

With lower clay contents, the B horizons of Podzols and Brown Podzolic soils also have lower base exchange capacities than Gray-Brown Podzolic soils. Lunt (1948) found capacities of 3 me. per 100 grams soil in B horizons of both groups. The data of Shaw and McKibben (1933) for Podzols in Quebec are similar in magnitude. On the other hand, Richard and Chandler (1943) found values of 40 me. per 100 grams soil in the B horizon of a Podzol containing approximately 10 per cent of organic matter. High capacities in B horizons of Podzols are associated with high contents of organic matter. For many Podzols and for most Brown Podzolic soils, the content of organic matter is low in the B horizon and the base exchange capacity is also low. Amounts of exchangeable calcium seem to run near 1 me. per 100 grams soil, whereas exchangeable magnesium is one-tenth to one-fifth of that amount. Exchangeable potassium is also low, generally much lower than exchangeable magnesium. Some soils have large amounts of exchangeable magnesium in the B horizons, as noted by Mitchell (1937). Base saturation in the B horizons of both Podzols and Brown Podzolic soils commonly ranges between 20 and 40 per cent though some soils fall on either side of this range. Because of the low levels of base saturation in B horizons of Podzols and Brown Podzolic soils, the available calcium, magnesium, and potassium are also low. On the other hand, the quantities and per cent saturation of exchangeable Ca and Mg and K in B horizons of Gray-Brown Podzolic soils are often high enough to furnish significant amounts of these nutrients for plant growth.

Most of the soil amendments used in crop productions are added to the surface layer of the soil. The movement of these amendments to deeper horizons is slow except for materials such as nitrates and sulfates. Consequently, the original differences in plant nutrient status between A and B horizons may be accentuated or obscured by fertilization and liming under cultivation. Where farms have been well managed and adequately fertilized for a number of years, the plant nutrient status of the A horizon has commonly been improved.

When the group of podzolic soils is considered collectively, the general levels of available plant nutrients in the B horizons are lower than those of A horizons. There are notable exceptions to the general rule, however, and these are of economic importance. Moreover, the large quantities of mineral plant nutrients present in B horizons of many soils represent a reservoir deserving of more study than it has received in the past.

*b. B Horizons of Latosolic Soils.* For this discussion, the latosolic soils include Latosols, formerly known as Laterites, Reddish Brown Lateritic soils and Yellowish Brown Lateritic soils (Marbut, 1930; Baldwin, Kellogg, and Thorp, 1938), Terra Rossa soils, and Red-Yellow Podzolic soils. These are the well-drained, forested, and savanna-covered soils of humid and wet-dry tropical and subtropical climates. These soils go round the world at the equator (Fig. 1) and constitute a large share of the land surface of the earth. They are represented in the southeastern United States by Red-Yellow Podzolic soils, as shown in Figs. 1 and 2. Despite their great extent, information regarding latosolic soils is limited. The soils of tropical and subtropical regions have thus far received much less than their proportionate share of attention from soil scientists.

The Latosols as a group are deeply and strongly weathered (Marbut, 1930; Mohr, 1944; Sherman, 1949; Kellogg, 1950). In spite of the intense weathering, however, the soils often lack distinct horizons except for a darkened surface layer. Beneath this surface layer, there is frequently little change in the profile to depths of several feet (Marbut, 1930; Roberts, 1942). The lack of distinct horizons is illustrated in the latosolic profile diagram in Fig. 3. Terra Rossa soils are morphologically similar to the Latosols but have undergone less intense weathering (Hollstein, 1938). Red-Yellow Podzolic soils are intermediate in their profiles between the latosolic and podzolic diagrams in Fig. 3. They resemble the podzolic soils in the upper profile or A horizon and the latosolic soils in the B and C horizons (Simonson, 1949). Because of similarities to Latosols in the major part of the profile, the B and C horizons, Red-Yellow Podzolic soils are discussed with the latosolic soils.

The Latosols, like the podzolic soils discussed in the preceding section, are geographically associated with a number of other different soil groups. For example, the latosolic zones in Fig. 1 include large and important areas of Alluvial soils in valleys of the Amazon, Congo, Ganges, and Mississippi Rivers. Many small areas of Alluvial soils exist along smaller streams. Ground-Water Laterite soils are also extensive, especially in Asia, Africa, and South America. The B horizons of Ground-Water Laterite soils are considered in a later section of this paper dealing with indurated or strongly cemented horizons. The Alluvial and Ground-Water Laterite soils are but two examples of the many soils associated with latosolic soils over their wide geographic range. Because of the great variety of soils in the latosolic zone, this discussion of B horizons cannot apply to all of them. The discussion applies mainly to the mature, well-drained soils and to a limited extent to the associated kinds.

Generally speaking, B horizons of latosolic soils are thick, have bright colors, and are high in free oxides, 1 : 1 lattice type clays, or both. Common thicknesses of B horizons are 3 to 4 ft., whereas the range is from about 1 to 10 ft. Colors are dominantly reddish, although some B horizons are yellow, yellowish brown, reddish brown, or brown. Most B horizons are high in free iron or aluminum oxides or both, and these may be partially segregated as concretions (Craig and Halais, 1934). The B horizons are commonly low in organic matter and nitrogen and seem to be about comparable in this regard to the podzolic soils. As compared to B horizons of podzolic soils, those of latosolic profiles are thicker, more strongly weathered, more friable, and less plastic. (Marbut, 1930; Hough and Byers, 1937; Holmes, Hearn, and Byers, 1938; Alexander, Byers, and Edgington, 1939; Roberts, 1942; Alexander, MacKenzie, and Moon, 1947; Kellogg and Davol, 1949; Sherman, 1949)

*(1) Physical properties.* Latosol B horizons are dominantly clay in texture (Bonnet, 1939; Sherman, 1949; Kellogg and Davol, 1949). Contents of clay commonly range above 50 per cent but occasionally are as low as 35 per cent though more often as high as 90 per cent. Although very high in clay, the B horizons are commonly friable and of low plasticity. Many of them show marked aggregation with high permeability and aeration capacity (Roberts, 1933). The soils, especially the B horizons, are strongly resistant to erosion. This was strikingly evident in the lack of cloudiness observed by one of the authors in irrigation water on Maui, in the Hawaiian Islands. The irrigation ditch was cut well into the B horizon of a Latosol on a 10 per cent slope. With that gradient, the water moved rapidly, but in spite of its rapid flow, the water was not carrying noticeable quantities of soil material. This Latosol in Hawaii has been formed from basic rock essentially devoid of quartz and has a high content of free oxides (Sherman, 1949). The resistance to erosion, together with the high permeability, seems to be associated with dominance of 1:1 lattice type clays and the high content of free oxides.

The B horizons of Red-Yellow Podzolic soils are less commonly clay in texture though they tend toward that end of the range. Sandy clay loams, clay loams, and sandy clays are common but loams also occur (Marbut, 1935; Holmes, Hearn, and Byers, 1938; Alexander, MacKenzie, and Moon, 1947; Templin, Martin, and Dyal, 1950). The B horizons of these soils are more plastic, less permeable, and more susceptible to erosion than the B horizons of Latosols. The clay fractions are usually high in 1:1 lattice type minerals, but other species are present in many instances (Pearson and Ensminger, 1948; Coleman, Jackson, and Mehlich, 1949; Dyal, Martin, and Templin, 1950).

The general character of B horizons of Red-Yellow Podzolic soils seems to be closely related to the nature of the parent material. One example will help clarify this relationship. The influence of parent material is strikingly evident among soils formed from limestone in the Great Valley of Tennessee (Hubbard, Matzek, and Jenkins, 1948). In the Great Valley, the limestones carry various kinds and amounts of impurities. Some approach pure calcite, some are moderately cherty, and some are highly argillaceous. The B horizons of Decatur soils, formed from "high grade" limestone, are dark red clay of moderate plasticity and permeability. The B horizons of Fullerton soils, formed from cherty limestones, are red clays with appreciable quantities of chert, perhaps a little more plastic than the Decatur soils. The Talbott soils, formed from slightly argillaceous limestone, have B horizons that are much more plastic and less permeable than those of Decatur and Fullerton soils. Where the limestone is highly argillaceous, Colbert soils are formed, which have more plastic and less permeable B horizons than Talbott soils. Moreover, the Colbert soils have much shallower profiles, apparently because of the plastic, impervious nature of the residuum from the argillaceous limestone. Similar relationships in character of the B horizon may be observed among Red-Yellow Podzolic soils formed from marine sediments of various textures. The Ruston soils formed from sandy sediments have less fine-textured and more friable B horizons than do the Boswell soils formed from clayey sediments.

Taking the group of latosolic soils as a whole, the B horizons range from very friable to firm and from slightly to moderately plastic. These horizons have more favorable physical properties, all in all, than the comparable horizons of podzolic and chernozemic soils. Generally, but not always, the physical properties of the B horizon are less favorable for plant growth than those of the overlying A horizon.

*(2) Clay minerals.* There is a wide range in latosolic soils from clay fractions which are mostly free oxides on the one extreme to clay fractions with some illite or montmorillonite on the other. On the whole, however, latosolic soils are moderate to high in free oxides and 1:1 lattice type clays but low or lacking in 2:1 lattice minerals.

In the study of a number of soils in Hawaii, Dean (1947) found that as much as 60 per cent of the clay fraction consisted of kaolinite. A large part of the remainder was free oxides although an appreciable residue was not identified. Quantities of kaolinite were commonly higher in B horizons than in the A horizons. Kellogg and Davol (1949) report from 20 to 60 per cent of the clay fraction as kaolinite in Latosols from the Belgian Congo in Africa. The dominance of kaolinite is also suggested by a base exchange capacity of 10 me. per 100 grams of soil in the Catalina clay of Puerto Rico (Bonnet, 1939). Similar evidence is available in the studies of buffering capacity of Hawaiian soils by Matsusaka and Sherman (1950). Some of the soils studied by Ayres (1943), however, have base exchange capacities higher than those of kaolinitic minerals and may contain other mineral species. Evidence of occurrence of other clay minerals in small amounts was reported for Latosols in the Belgian Congo by Kellogg and Davol (1949).

The possible quantities of free oxides in the clay fractions of latosolic soils are indicated by data of Goldich and Bergquist (1948) for an aluminous lateritic soil in Haiti. The clay fraction contained from 5 to 10 per cent of kaolinite, whereas the soil was 60 per cent gibbsite and bohemite. The soil in Haiti, like the ferruginous humic Latosols studied by Sherman, Foster, and Fujimoto (1948) in Hawaii, represents an extreme degree of weathering of Latosols. For the most part, the clay fractions of Latosol B horizons contain moderate to high proportions of free oxides and kaolinite.

The clay fractions of Red-Yellow Podzolic soils are normally lower in free oxides than the Latosols, but there is some overlapping. They are also kaolinitic, for the most part, though 2:1 lattice type minerals are present in many soil types. According to Pearson and Ensminger (1948), the clay fractions from B horizons of several Red-Yellow Podzolic soils in Alabama consist of 30 to 50 per cent of kaolinite and 12 to 17 per cent of free iron oxides. These soils contain variable quantities of hydrated aluminum oxides. Similar compositions of the clay fraction were found earlier by Alexander, MacKenzie, and Moon (1947) in a study of soils of the Great Valley of Tennessee and Virginia. The soils from the Great Valley are high enough in potassium contents to suggest the presence of illite. The occurrence of illite in significant amounts has also been reported by Coleman, Jackson, and Mehlich (1949) and Dyal, Martin, and Templin (1950) in Red-Yellow Podzolic soils formed from crystalline rocks in the Piedmont and from marine sediments in the Coastal Plain of the southeastern United States. By and large, the clay minerals of Red-Yellow Podzolic soils seem to be dominantly kaolinitic, with free oxides generally present but with significant quantities of 2:1 lattice type minerals present in many instances.

As compared to podzolic and chernozemic soils, latosolic B horizons are higher in free iron and aluminum oxides such as goethite, gibbsite, and hematite; higher in 1:1 lattice type minerals; and lower in 2:1 lattice type minerals.

*(3) Fertility levels.* Like the B horizons of podzolic soils, those of latosolic soils may be either higher or lower in plant nutrients than the A and C horizons. The data of Hough and Byers (1937) show only slight changes with depth in the total contents of calcium, magnesium, phosphorus, and potassium in Latosols of Hawaii. Total analyses of Red-Yellow Podzolic soils indicate increases with depth in some profiles and decreases in others (Marbut, 1935). The data available for latosolic soils show no consistent differences in total contents of mineral plant nutrients between the A, B, and C horizons. For the same soils, however, the contents of organic matter and nitrogen are lower in the B horizon than in the A horizon.

Contents of organic matter commonly range from 0.2 to 2 per cent in latosolic B horizons (Brown and Byers, 1938; Goldich and Bergquist, 1948; Kellogg and Davol, 1949). In a fair number of Latosols, organic matter comprises as much as 3 per cent of the upper B horizon and in a very few, it ranges up to 5 or 6 per cent (Hough and Byers, 1937). Soils with the high contents of organic matter in the B horizon are uncommon, however, and seem to be restricted to regions of high rainfall. In a majority of the soils, contents of organic matter are below 1 per cent in the B horizon. Amounts of nitrogen are commonly about 5 per cent of the content of the organic matter, or 0.01 to 0.1 per cent. Contents of nitrogen as high as 0.52 per cent have been reported, however, in Latosols of high rainfall zones (Ayres, 1943).

The total quantities of phosphorus (as $P_2O_5$) in the B horizons of latosolic soils commonly equal about 0.1 per cent of the soil. In general, the content of phosphorus is equal to or slightly lower than those of the adjacent A and C horizons (Hough and Byers, 1937). Because organic matter is low, the amounts of phosphorus in organic form are also generally low. There are some exceptions among the Latosols. Dean (1937) found 25 per cent of the total phosphorus in organic form in a Latosol profile from Hawaii. Comparable amounts of organic phosphorus seldom occur in the B horizons of soils in the latosolic group. Garman (1948) found that 13 per cent of a total quantity of 100 p. p. m. of phosphorus were in organic form in the subsoil of Bowie very fine sandy loam, a Red-Yellow Podzolic soil. Quantities of phosphorus in available form are low to very low in the B horizons of these soils. The high contents of free oxides reduce the availability of phosphates generally and introduce numerous problems in the effective use of phosphatic fertilizers.

Base exchange capacities of latosolic B horizons are usually low to medium, depending on the amounts of organic matter present. Base saturation is also generally low. The amounts of exchangeable calcium, magnesium, and potassium are small as compared to hydrogen. Kellogg and Davol (1949) report base saturations ranging from 8 to 20 per cent in the B horizons of Latosols in the Belgian Congo. Amounts of exchangeable bases per 100 grams soil were 0.1 to 2.0 me. of calcium, 0.1 to 0.5 me. of magnesium, and about 0.1 me. of potassium. Data of Bonnet (1939) for the B horizon of Catalina clay are of the same order of magnitude. The capacities reported by Ayres (1943) for soils of high rainfall areas in Hawaii are much higher, but nearly all the samples seem to fall within the A horizon. Among the samples taken from the subsoil, some seem to be parts of the B horizon. Data for these samples are comparable to those from the Belgian Congo, and some of the soils studied by Ayres (1943) also seem to be Latosols. Further support is lent this interpretation by the data for exchangeable potassium in profiles of Latosols and certain other groups in Hawaii (Ayres, Hagihara, and Fujimoto, 1949). Matsusaka and Sherman (1950) state that base saturation and exchange capacities are low to very low in the Latosols which have reached moderate to advanced stages of weathering. High exchange capacities can be expected in Latosol B horizons high in organic matter, but such soils do not seem to be common or widespread.

The base exhange capacities and the base saturation of B horizons of Red-Yellow Podzolic soils, as reported by Dyal and Drosdoff (1943), are comparable to those of Latosols. Considering possible averages for the two groups of soils, it seems that the Red-Yellow Podzolic soils would have slightly higher base exchange capacities and base saturation. Actual differences or lack of them between examples of the groups would depend upon the texture of the soil materials and upon the stage or intensity of weathering. Ranges of exchangeable bases per 100 grams soil were 0.1 to 6.0 me. of calcium, 0.1 to 3.0 me. of magnesium, and 0.02 to 0.4 me. of potassium. Base saturation seems to have a range of about 3 to 60 per cent. For the most part, the soils are moderately to strongly acid.

Base exchange capacities of the B horizons of latosolic soils are usually about the same as the overlying A horizons. Clay minerals in these soils commonly have fairly low capacities and, as a result, the higher contents of clay in the B horizon are offset by higher contents of organic matter in the A horizon. The A horizons of Latosols in very humid regions are extremely high in organic matter and have base exchange capacities much greater than those of underlying horizons. Similarly, the base exchange capacity of the surface layer is far greater than that of subsoil layers in the sandier soils of Red-Yellow Podzolic regions.

The effects of past management on the status of exchangeable calcium, magnesium, and potassium is discussed by Ayres (1943) for a number of soils in Hawaii. Data are primarily for surface soils but a few subsoils have been included. The conclusions with regard to the changes in A horizons seem to be valid as well for underlying B horizons. The study shows that exchangeable calcium is unchanged, that magnesium has been reduced, and that potassium has been increased. Thus, there is no consistent pattern in depletion or increase of available mineral nutrients. Similar situations can be expected for most latosolic soils. Shifts in fertility status are down in some cases and up in others. The fertility status will have been raised in many instances, however, because of the original low base levels.

*c. B Horizons of Chernozemic Soils.* Chernozemic soils comprise the black, brown, and dark gray ones of grasslands in temperate and tropical climates. As shown in Fig. 1, these soils cover large areas in Asia, Africa, Europe, and North America. They cover smaller but important areas in South America and Australia as well. In the subhumid and semi-arid temperate zones, chernozemic soils include the Prairie, Chernozem, Chestnut, Reddish Prairie, and Reddish Chestnut soils. These are shown for the United States in Fig. 2. In tropical and subtropical regions, this group includes dark gray to black soils of wet-dry savannas known by names such as regur, tirs, black cotton soils, black turf soils, and vlei soils (Oakes and Thorp, 1950). The Chernozem, Chestnut, and Reddish Chestnut soils are major wheat-producing regions in the United States and the Prairie soils are the heart of the Corn Belt (Marbut, 1931). The Chernozem and Chestnut soil belts are of prime importance in the production of grains in Russia (Marbut, 1931), whereas the Prairie soils have similar importance to the agriculture of Argentina (Vessel, 1946). It has been estimated that the dark-colored soils of the temperate grasslands now produce about 90 per cent of the grain moving through commercial trade channels. Dark-colored soils of the tropics and subtropics have less importance to agriculture generally (van der Merwe, 1949; Griffith, 1949). The name, ''black cotton soils'' (Robinson, 1949), indicates their use in parts of Africa and India. For the most part, the soils seem to be used for grazing and the like, with large areas in native reserves. (Basu and Sirur, 1938; Desai, 1938; van der Merwe, 1940; Thorp, Williams, and Watkins, 1948; Mitchell and Moss, 1948; Smith, Allaway, and Riecken, 1950)

Features common to chernozemic soils are dark color and great thickness of A horizon, a low degree of weathering, and medium to high levels of fertility. The general characteristics of the soils are illustrated by the chernozemic profile in Fig. 3. The lime zone shown in this profile occurs in most Chernozem, Chestnut, and Reddish Chestnut soils and also in most of the black clay soils of the tropics and subtropics. It is commonly absent from the profiles of Prairie and Reddish Prairie soils. In temperate regions, the A and B horizons are thickest in the Prairie soils and become thinner with decreasing rainfall across the Chernozem and Chestnut zones. The A horizons are especially thick in the dark clays of subtropical regions, partly because of the formation and filling of deep cracks (van der Merwe, 1949). Because of the cracking and crumbling, these soils have been called self-mulching or self-swallowing clays in some areas.

Chernozemic B horizons are chiefly transitional layers between the A horizons high in organic matter and the C horizons of parent material. The B horizons are commonly marked by more distinct structure, either prismatic or blocky, in the Chernozem, Chestnut, and Reddish Chestnut soils. The B horizons of Prairie and Reddish Prairie soils are generally higher in clay than the A or C horizons. B horizon boundaries in chernozemic soils are diffuse except in dark tropical clays, where they are said to be sharp (van der Merwe, 1949). Thickness of B horizon ranges from a rough average of 1 ft. in the Chestnut soils and dark tropical clays to about 2 ft. in Prairie and Reddish Prairie soils. As compared to those of podzolic soils, the B horizons are less acid, lower in free oxides, and higher in 2:1 lattice type clays. They are about equally thick in the two groups of soils. B horizons of chernozemic soils are much thinner, on the average, than those of latosolic soils. They are also much lower in free oxides, much higher in 2:1 lattice type minerals, and commonly less friable and more plastic. Chernozemic B horizons are slightly thicker and slightly higher in organic matter than those of desertic soils.

*(1) Physical properties.* Among the B horizons of chernozemic soils, there are wide ranges in texture, consistence, and permeability, depending upon the degree of horizon differentiation and the original character of the soil material. By and large, Chernozem, Chestnut, and Reddish Chestnut soils lack fine-textured B horizons, and this is also true for a majority of the Prairie and Reddish Prairie soils. There are Prairie soils, however, with B horizons high in clay. Clay textures are normal in the dark tropical and subtropical soils.

The B horizons of most Chernozem, Chestnut, and Reddish Chestnut soils and of many Prairie soils are clay loams or silty clay loams (Brown and Byers, 1935; Mitchell and Riecken, 1937; Larson, Allaway, and Rhoades, 1947; Hutton, 1947; Smith, Allaway, and Riecken, 1950). Excluding a very few soils, the range in texture extends from sandy loam to sandy clay. As a rule, the B horizons are higher in clay than the A and C horizons though the differences in themselves are seldom significant. The strong nutrient cycle of grass vegetation, coupled with geologic youth of parent materials in many places, has not yet permitted much clay formation in the soils and has kept the colloids in the upper horizons flocculated. Despite the generally small differences in texture between the A and B horizons, there are considerable differences in consistence and permeability. B horizons are decidedly less friable and more plastic than the overlying A horizons, because of the lower contents of organic matter. They are also firmer and more plastic than the C horizons. Structure of the B horizon is commonly prismatic in Chernozem, Chestnut, and Reddish Chestnut soils, whereas it is more often blocky in the Prairie and Reddish Prairie soils.

With increasing soil age, the passage of more water through the profile, or finer texture of parent materials, the clay contents of the B horizons tend to increase. The studies by Smith (1942) in Illinois and by Hutton (1947) in Iowa indicate that B horizons of Prairie soils become finer-textured as effective age increases. Maximum clay contents in the B horizon range from 10 per cent in young Prairie soils from loess in western Iowa up to 50 per cent in the older Prairie soils from loess in the south-central part of the state (Hutton, 1947). Similarly, the clay contents in the B horizons of soils on the more level to slightly depressed positions in eastern Nebraska are higher than those in soils of convex slopes (Smith and Rhoades, 1942a). The effects of texture of parent material on the B horizon have been studied in soils formed from glacial till in central Illinois by Stauffer (1935) and Wascher and Winters (1938). They report a close correlation between the texture and permeability of the B horizon with the physical composition of the underlying glacial till. As the clay content of the till increases, the B horizons become finer textured and more slowly permeable.

The dark soils of tropical and subtropical regions seem to be chiefly clays throughout the profile (van der Merwe, 1940; Desai, 1938). These soils are said to be similar to the Houston Black clay in Texas (Oakes and Thorp, 1950). Van der Merwe (1940) describes a thin B horizon which is essentially a gradation between the unusually thick A horizon and the underlying parent material. Evidently the B horizon is of minor consequence. Like the rest of the profile, it exhibits marked shrinking and swelling, is very plastic, and appears to be slowly permeable.

Chernozemic B horizons have less favorable physical properties for plant growth than do the A horizons. This follows from their higher plasticity and lower friability, for the most part. Available information suggests that physical properties are likely to be more troublesome than the nutrient status of these horizons in their relationships to growing plants.

*(2) Clay minerals.* The B horizons of chernozemic soils contain 2:1 lattice type minerals, as a rule, and are low in free oxides. The montmorillonite and illite groups are both represented, as indicated by the studies of Clark, Riecken, and Reynolds (1937); Alexander, Hendricks, and Nelson (1939); Russell and Haddock (1940); and Larson, Allaway, and Rhoades (1946). These minerals are also dominant in the clay fractions of dark tropical and subtropical soils (Nagelschmidt, Desai, and Muir, 1940; van der Merwe, 1949). The prevalence of the 2:1 lattice type clay minerals seems to be a reflection of the low degree of weathering common to so many of the soils.

Although clay minerals of the 2:1 lattice type predominate, others are present in small quantities in a number of soils. Clark, Riecken, and Reynolds (1937) report the occurrence of some kaolinite in profiles of Chernozems and Chestnut soils in Saskatchewan. Peterson (1946b) found kaolinite in some Prairie soils in Iowa, especially in those formed from shaley parent materials. Wherever parent materials are high in kaolinite, chernozemic soils can also be expected to contain the clay mineral in appreciable quantities. Along with the silicate clay minerals in the B horizons, there is usually some quartz and some free oxides in the clay fractions. From 2 to 3 per cent of free iron oxides have been reported in the profiles of Prairie soils by Hutton (1947). Caldwell and Rost (1942) suggest some accumulation of iron in the B horizons of Prairie and Gray-Brown Podzolic soils but not in Chernozems. Quantities of free iron oxides noted in Prairie B horizons are much lower than those found in comparable horizons of Red-Yellow Podzolic soils by Pearson and Ensminger (1948).

The dominance of clay minerals of the 2:1 lattice type in chernozemic B horizons is reflected in the physical characteristics, in base exchange relations, and in fertility status generally. The B horizons are notably plastic for any given texture; they shrink and swell appreciably; and they generally have high exchange capacities and high base saturation.

*(3) Fertility levels.* The plant nutrient status of chernozemic B horizons compares favorably with those of the A and C horizons in many respects. Supplies of plant nutrient elements are commonly medium to high except for nitrogen and sulfur, which are appreciably lower in the B than in the A horizon. The amounts of nitrogen and sulfur parallel the content of organic matter. The total quantities of calcium, magnesium, and potassium are generally high, and the levels of exchangeable calcium, magnesium, and potassium are also high for most chernozemic soils.

Even though contents of organic matter and nitrogen are lower in the subsoil layers than in the surface soil, they are still appreciable. Quantities of organic carbon ranging between 1 and 2 per cent of the soil are common in medium-textured B horizons of Prairie soils and Chernozems (Marbut, 1935; Mitchell and Riecken, 1937; Whiteside and Smith, 1941; Smith, Allaway, and Riecken, 1950). The quantities are somewhat lower in B horizons of Chestnut, Reddish Chestnut, and Reddish Prairie soils (Marbut, 1935). They are of the same order of magnitude in the tropical and subtropical dark clay soils (van der Merwe, 1940). The amounts of nitrogen, organic phosphorus, and sulfur parallel those of organic matter, as a general rule. Nitrogen contents of the B horizons are commonly less than 0.1 per cent but range down to 0.02 per cent in the subtropical dark clays.

The total quantities of phosphorus are relatively high in the chernozemic soils of temperate zones (Marbut, 1935), if sandy soils are excluded. In contrast, they are commonly low in the tropical and subtropical soils as indicated by analyses of van der Merwe (1940). Total quantities of phosphorus (as $P_2O_5$) range from 0.1 to 0.3 per cent in the B horizons of Chernozems, Chestnut, and Reddish Chestnut soils (Marbut, 1935) and are slightly lower in Prairie soils (Pearson, Spry, and Pierre, 1940). In Prairie soil B horizons organic phosphorus makes up less than one-fourth of the total, whereas dilute-acid soluble phosphorus may be as high or higher (Pearson and Simonson, 1939). Amounts and proportions of organic phosphorus in the B horizons of Prairie soils are much lower than those in A horizons. Similar amounts of organic phosphorus occur in B horizons of Chernozem and Chestnut soils (Odynsky, 1936) with smaller amounts probable in Reddish Chestnut, Reddish Prairie, and dark subtropical soils. Experiments indicate that the dilute-acid soluble phosphorus is available to plants such as sweet clover (*Melilotus*, spp.) but not to corn (*Zea mays*). Quantities of phosphorus present in all forms are significant, however, in that some can be tapped now and all represent possible reserves for future plant growth.

The amounts of exchangeable calcium, magnesium, and potassium and the base saturation are high in the B horizons of most chernozemic soils. In Prairie soils of Iowa and Illinois, the quantities per 100 grams soil in the B horizons range up to 15 me. of calcium, 6 me. of magnesium, and 0.56 me. of potassium (Whiteside and Smith, 1941; Hutton, 1947; Smith, Allaway, and Riecken, 1950). Amounts present are of the same order of magnitude in the Chernozem and Chestnut soils studied by Mitchell and Riecken (1937) in Saskatchewan. Ulrich (1950) has reported exchangeable potassium levels in Prairie subsoils in Iowa that exceed in many cases the levels in the surface soils. The common range in base saturation of the B horizons of Prairie and Reddish Prairie runs from 50 to 90 per cent, depending upon the degree of weathering, whereas it usually approaches 100 per cent in the Chernozem, Chestnut, and Reddish Chestnut soils.

In three profiles of subtropical black soils studied by van der Merwe (1940), the B and lower A horizons had extremely high base exchange capacities despite low contents of organic matter. Exchangeable calcium and magnesium together range from 36 to 50 me. per 100 grams soil in the B and lower A horizons. In two profiles, there were 25 to 40 me. calcium and 8 me. magnesium per 100 grams of soil, whereas in the third there were 40 me. magnesium and about 3 me. calcium. Exchangeable potassium levels were between 0.25 and 0.60 me. per 100 grams of soil in the same part of the profile.

The levels of exchangeable calcium, magnesium, and potassium in the B horizon are high in chernozemic soils as compared with podzolic and latosolic soils. The quantities are several times as great, as a general rule. Although data on desertic soils are limited, it seems that the levels in the B horizons of those soils will be somewhat lower in magnitude.

In addition to calcium and magnesium present in exchangeable form, a lime zone, illustrated in Fig. 3, commonly occurs in the subsoils of Chernozem, Chestnut, Reddish Chestnut, and subtropical black clay soils (Marbut, 1935; Desai, 1938; van der Merwe, 1949). Lime zones have also been found in some of the younger Prairie soils (Smith, Allaway, and Riecken, 1950). The depth at which the lime zone occurs in soils from similar parent material is related to rainfall in the Great Plains (Jenny and Leonard, 1934). As the rainfall increases from west to east, the average depth to carbonate along an isotherm also increases. Because of the lime zone, large quantities of calcium and smaller ones of magnesium are commonly within reach of plant roots (Thiel and Sherman, 1938).

The subsoils of chernozemic soils contain substantial reserves of calcium, magnesium, and potassium, as well as smaller reserves of phosphorus. These are of especial importance to certain legume crops which require large quantities of potassium. For example, heavy removal of potassium by alfalfa (*Medicago sativa*) can be carried on for a long period without depleting soil reserves unduly. At the same time, there is some evidence of depletion of more available forms of phosphorus in the sharply increased interest in fertilizer in the Corn Belt and Great Plains during the past few years. With the very large quantities of mineral plant nutrients present in the B horizons of chernozemic soils, these subsoils are of special interest as possible sources of those elements. Further studies of ways and means to utilize the reserves effectively for plant growth seem highly desirable.

*d. B Horizons of Desertic Soils.* The desertic soils are light colored, unleached soils of arid, temperate, and tropical lands. They commonly carry sparse shrub or grass vegetation. They are the mature or zonal soils in the immense deserts of Africa, Asia, and Australia shown in Fig. 1. They are present in smaller areas in North and South America. For this discussion, the desertic soils include the Brown and Reddish Brown soils as well as the Sierozems or Gray Desert soils and the Red Desert soils of the western United States (Fig. 2).

Because of limited rainfall, the desertic soils have been subject to very little leaching. Furthermore, low precipitation has restricted plant growth so that soils are low in organic matter. The mature or zonal soils are marked by horizons differing more in structure, consistence, and texture than in color or chemical composition (Nikiforoff, 1937). The general features of the soils are illustrated in the desertic profile diagram in Fig. 3. This diagram represents the group of Desert soils, whereas the group of Brown and Reddish Brown soils are intermediate between this diagram and that of chernozemic profiles. Lack of a thick, dark A horizon and the presence of a lime zone nearer the surface are features that set the desertic soils apart from the typical Chernozems.

Special attention should be called to the large areas of shallow and stony or rocky soils, the wide distribution of rockland, and the great sand wastes in large deserts. Lands without evident soil profiles are extensive components of desert landscapes generally. They are probably more extensive than the zonal soils. For example, all of them are emphasized in the discussion of the Sahara Desert by Gautier (1935) and in the soil map of Africa prepared by Schokalsky (1944). Special mention is made by Nikiforoff (1937) of the rockland and the rocky, shallow soils in the Mojave Desert. Soils that are shallow and rocky as well as the deep sands lack evident B horizons. Furthermore, the sands, the shallow stony soils, and the rockland have little or no importance to plant growth. Consequently, no further attention will be given to them in this paper.

The B horizons of desertic soils are chiefly transitional layers between the A and C horizons, often higher in clay than either of the others. The differences in clay contents are not marked, but they seem to occur in many profiles (Thorp, 1931; Nikiforoff, 1937; Brown and Drosdoff, 1940). Desertic B horizons usually have more distinct structure, especially in Brown and Reddish Brown soils, and are less friable than the A and C horizons. Thicknesses are commonly between 3 and 8 in. but range up to a foot. As compared to chernozemic soils, desertic soils have thinner B horizons which are lower in organic matter. They have much thinner B horizons higher in 2:1 lattice type minerals and lower in free oxides than latosolic soils. They have thinner B horizons lower in organic matter and free oxides but higher in 2:1 lattice type minerals than podzolic soils.

*(1) Physical properties.* The limited data on B horizons of desertic soils suggest that the ranges in texture, consistence, and the like are slightly narrower than those in chernozemic soils. This may be apparent rather than real, however, because information is at hand for very few profiles. The B horizons for which field descriptions, mechanical analyses, or both are available commonly range from loam to clay loam, with a few sandy loams, and sandy clays (Thorp, 1931; Brown and Byers,

1935; Brown and Drosdoff, 1940; Orvedal, Kubota, and Smith, 1951). Textures outside of the common ranges seem to be important where the Desert soils grade into the deep sands. Although the B horizons are commonly finer textured than the A and C horizons, the differences are not large. Even so, the B horizons are less friable and more plastic than the A and C horizons. The distinction between the A and B horizons in consistence is more a reflection of organic matter content than of texture.

On the whole, the content of clay in the B horizons of desertic soils is not high, nor is the total quantity in the entire profile high. With the limited supplies of moisture available in desert regions and bordering lands, the rates of clay formation and of horizon differentiation should be much slower than in humid regions. Given sufficient time without changes in the land surface, however, much clay as well as distinct horizons can be formed (Nikiforoff, 1937). Despite the possibilities of clay formation and development, they would hardly be common since disturbance can be expected in most soils.

*(2) Clay minerals.* The colloid fractions in Desert soils formed from granite in the Mojave Desert are about 75 per cent 2:1 lattice type and 25 per cent 1:1 lattice type minerals (Brown and Drosdoff, 1940). Similar mineralogical composition of clay fractions in Desert soils have been reported by Alexander, Hendricks, and Nelson (1939). These proportions are similar to the common ones in chernozemic soils. (See Section III 1c). With the similarities in clay mineral kinds between the Desert and Chernozem soils, it can be assumed that those in the Brown and Reddish Brown soils would also be similar. Like the B horizons of chernozemic soils, those of desertic soils might also be high in 1:1 lattice type minerals, especially in soils formed from parent material such as kaolinitic shale. In addition to silicate clay minerals, Brown and Drosdoff (1940) report small quantities of free iron oxides in the colloid fractions of Desert soils. The amounts noted are similar to those in Prairie soils (Hutton, 1947). It seems probable that quartz and some micas, and perhaps calcite in a few instances, also occur in the clay fractions of desertic soils.

*(3) Fertility levels.* In B horizons of desertic soils, total quantities of some plant nutrients are higher and others lower than in the A horizons. The totals for calcium, magnesium, and potassium are commonly, though not always, higher (Marbut, 1935; Brown and Byers, 1935). The amounts of nitrogen and sulfur are consistently lower, whereas those of phosphorus are erratic. Exchangeable calcium, magnesium, and potassium are medium to high, but available phosphorus seems to be generally low (Mitchell and Riecken, 1937; Brown and Drosdoff, 1940).

The amounts of organic matter in the B horizons of desertic soils are extremely low. Quantities reported for Desert soils by Brown and Drosdoff (1940) fall near 0.2 per cent, whereas those in Brown soils are slightly higher (Brown and Byers, 1935). The common range for medium-textured B horizons, for the group as a whole, seems to be from 0.2 to 0.5 per cent. Along with their low contents of organic matter, these soils are also low in nitrogen, sulfur, and phosphorus in organic forms. Quantities of nitrogen are about one-tenth those of organic carbon, whereas the amounts of sulfur and organic phosphorus are negligible.

High levels of exchangeable calcium and magnesium in the B horizons are reported for Desert soils by Brown and Drosdoff (1940) and for Brown soils by MacGregor and Wyatt (1945). Quantities present are of the same order of magnitude as those in B horizons of chernozemic soils. Although few data are available, it seems certain that high levels of exchangeable calcium and magnesium prevail in desertic B horizons. They are to be expected under the conditions of limited rainfall and restricted leaching which dominate formation of the soils. The amounts of exchangeable potassium reported by Brown and Drosdoff (1940) are somewhat lower than commonly found in chernozemic soils. As with calcium and magnesium, however, fairly high relative levels are to be expected, though the absolute levels will be much lower. In addition to the amounts of calcium and magnesium present in exchangeable form, there are also large amounts in the carbonate accumulations in many desertic soils. These lime zones lie nearer the surface than those of Chernozem and Chestnut soils. Most of them lie within reach of plant roots, and many of them are high enough in carbonates to interfere with uptake of phosphorus, iron, and other elements from the calcareous layers.

In summary, it can be said that the fertility levels of B horizons of desertic soils generally are medium to low. Available calcium and magnesium are usually plentiful in the B horizons, and there may also be good supplies of potassium. By way of contrast, the amounts of nitrogen, sulfur, and available phosphorus are low. The plant nutrient status under natural conditions will support the native vegetation with few signs of deficiencies, but the limited supplies of nitrogen and phosphorus become strikingly evident when soils are put under irrigation. These nutrient elements are not often limiting in the production of dry-land crops on Brown and Reddish Brown soils. On those soils, however, the growing of crops is normally successful in seasons with more than average rainfall. Long-time, heavy cropping of such soils can also be expected to develop deficiencies of nitrogen and phosphorus.

### 2. *Pan Layers*

The character of pans is of three general types: horizons or layers of clay accumulation, compact horizons or layers without definite cementation, and horizons or layers with definite cementation. The three types are called claypans, fragipans, and hardpans in this discussion. Hardpans are further subdivided into the ortstein layers of Ground-Water Podzols, the laterite crusts of Ground-Water Laterite soils, the iron-silica pans of dry regions, and the caliche or calcareous pans of dry regions.

Pan layers commonly occur in the intrazonal soils that occupy gentle slopes or level sites subject to excess moisture without being under water except for brief periods of time. There are some exceptions, as for example, the fossil laterites in western Australia. In many such instances, however, it seems that the pan layers were formed in smooth landscapes under the influence of excess water. Other possible exceptions are the iron-silica pans in dry regions, the exact origins of which are not clear. Still others are heavy clay layers that are not related to past or current cycles of soil development. Although intrazonal soils with pans of various kinds frequently have some characteristics in common with associated zonal groups, they are set apart by the horizons or layers that interfere with root and water penetration.

*a. Claypans.* The term ''claypan'' refers to a horizon or layer in the soil profile that is plastic and slowly pervious because of an unusually high clay content. Such horizons have also been called plastic pans and ''argipans.'' Most commonly, claypans are the genetic B horizons of certain Planosols and Solonetz soils. The high clay contents in such B horizons are due in part to formation of clay in place and in part to movement of clay from the overlying A horizons. Occasionally, however, unconforming fine-textured layers in stratified sediments, glacial till, and the like function as claypans within the profile. Despite the fact that they are commonly genetic B horizons, claypans are discussed separately because they offer special problems in subsoil permeability.

*(1) Distribution.* Planosols with claypan B horizons are extensive on the smooth lands of the Prairie and Gray-Brown Podzolic regions of the United States (Fig. 2). They are especially widespread in northern Missouri and southern Illinois. They are also dominant parts of the soil pattern in sections of Indiana, Iowa, Kansas, Oklahoma, and Nebraska. In the Gray-Brown Podzolic region, they extend into Pennsylvania and New York. Furthermore, they extend westward from the Prairie region into the more humid portions of the Chernozem belt. Planosols with claypan B horizons are widely distributed but seldom occur in as large

areas in the Red-Yellow Podzolic region of the southern United States. The Iredell series from basic igneous rock and the Lufkin series from acid clays in the Gulf Coastal Plain are good examples. Planosols with claypan B horizons have also been described in China by Thorp (1939) and in Japan by Whiteside (1950). Claypans have been reported in India (Mukherjee and Carbery, 1937) and they seem to be present in the "shoal" soils described by Hardy and Rodrigues (1941) in the West Indies. These observations in various parts of the world suggest that Planosols with distinct claypans will be found far more widely as field study and mapping of soils proceeds. Wherever found, the soils have special management problems because of low subsoil permeability.

The Solonetz and solodized-Solonetz soils have a geographic occurrence in part overlapping that of Planosols and also resemble them in certain profile characteristics. The B horizons of Solonetz and solodized-Solonetz soils closely resemble and often function as claypans. These soils are associated with Planosols to some extent in the chernozemic zone (Thorp, Williams, and Watkins, 1948) and in southern Illinois (Smith, 1937). Solonetz and solodized-Solonetz soils occur as characteristic parts of the soil pattern in many places in the Chernozem, Chestnut, Reddish Chestnut, Brown, Reddish Brown, and Desert soil zones in the United States (Fig. 2). They have been described and studied in many of the western states (Storie, 1933; Isaak, 1934; Kellogg, 1934; Rost, 1936; Fitts, Rhoades, and Lyons, 1939). Solonetz soils also occur widely in the provinces of western Canada (Odynsky, 1945; Mitchell and Moss, 1948). Soils with the morphology of solodized-Solonetz are described in the soil survey report for Livingston Parish, Louisiana (Anderson *et al.*, 1936). The occurrence of such profiles in humid regions, however, is generally uncommon, whereas the soils are common in the landscapes of arid, semi-arid, and subhumid regions. Solonetz and solodized-Solonetz soils have been reported in most drier parts of the world, as for example in Africa, Australia, and Asia (Vilensky, 1935; Ellis, 1949; Stephens, 1950).

From the point of view of their behavior under cultivation, there are a number of soils with claypans which are not genetic B horizons. These soils are formed from stratified sediments or from parent material in which there is a marked unconformity within the profile. Examples are the Susquehanna, Tickfaw, and Vaiden series of the southeastern United States and the Clarence series in north-central Illinois. The Susquehanna, Tickfaw, and Vaiden soils have all been formed from stratified marine sediments with or without thin overlying deposits of other materials. The Tickfaw soils consist of shallow loess over thick beds of clay, whereas the Vaiden soils may or may not have thin sandy or silty surface layers overlying heavy clays. The Susquehanna soils have been formed from thick beds of acid heavy clays with or without thin overlying sandier strata. In all of these soils, the fine-textured subsoil functions as a claypan. This is also true of the Clarence series formed from shallow loess over heavy glacial till in the region of Prairie soils in Illinois. These and similar soils in which the present profile is in part inherited from a past geologic era are essentially comparable to Planosols with claypans in so far as plant growth is concerned.

*(2) Physical properties.* The B horizons of Planosols (with claypans) and Solonetz soils are high in clay, have prismatic or blocky structures, as a rule, and are extremely plastic. Comparisons of a Planosol profile with certain other intrazonal soils and with a Gray-Brown Podzolic profile are indicated in Fig. 4 on p. 11 (Kellogg, 1936). The topographic relationships shown are common but not universal for Planosol and Solonetz soils.

Thickness of B horizon, on the whole, is less in Planosols than in associated zonal soils. Planosol B horizons are usually 1 to 2 ft. thick but may be either slightly thinner or thicker. Solonetz B horizons are commonly 1 to 1½ ft. thick. The extreme range in thickness of claypan is much greater when the nongenetic claypans are included. These layers may be many feet in thickness, as in the Susquehanna and Clarence soils.

The clay contents of Planosol B horizons commonly range between 40 and 60 per cent. Whiteside (1944) reported 58 per cent of clay in the B horizon of Putnam silt loam, whereas Ulrich (1949) found 52 per cent in the corresponding horizon of Edina silt loam. More than half of the entire clay fraction in the two B horizons was finer than 0.06 micron. Similar percentages of clays in the B horizon have been reported for the Butler, Crete, and Fillmore soils in Nebraska (Brown, Rice, and Byers, 1933; Smith and Rhoades, 1942b) and for the Iredell and Lufkin soils of the southeastern United States (Lutz, 1934; Marbut, 1935).

The contents of clay in B horizons of Solonetz soils are generally slightly lower than in Planosols. The common range seems to be between 25 and 45 per cent although some B horizons are as high as 55 per cent (Brown, Rice, and Byers, 1933; Kellogg, 1934; MacGregor and Wyatt, 1945; Riecken and Stalwick, 1945).

The order of magnitude of clay contents in nongenetic claypans are comparable to those of Planosol B horizons. The deeper layers of Susquehanna soils contain 45 per cent of clay (Pearson and Ensminger, 1948) whereas those of Clarence soils are 57 per cent of clay.

Low permeabilities are outstanding features of claypan horizons or layers. Ulrich (1949) reports an aeration porosity of 5.6 per cent and a permeability of 1.7 in. of water per hour for the $B_2$ horizon of Edina silt loam. These values are one-fourth or less of those for B horizons of youthful Prairie soils. The amount of pore space at different degrees of wetness in the B horizons of Planosols of eastern Nebraska also indicate low permeabilities (Smith and Rhoades, 1942b). Riecken and Stalwick (1945) found low permeabilities in the B horizons of Solonetz soils. A given quantity of water took 15 times as long to pass through a sample of the B horizon of a Solonetz as it did through a comparable sample of an associated Brown soil. Further evidence of the low permeability of claypan horizons is the local movement of water outward on the face of slopes at outcrops of Planosols formed from glacial drift now buried by loess in Iowa. These outcrops become local seep spots in the spring, and many of them are marked by slip scars where water-saturated soil material has moved downslope over the B horizon of a buried profile (Aandahl and Simonson, 1950).

The density and low porosity of claypans are also indicated by the difficulties of root penetration. In studies of distribution of grass roots in the Prairie and related soils of eastern Nebraska, Weaver and Darland (1949) found that the fibrous roots were markedly fewer in the B horizon than in either the A or C horizons of Butler soils. On the other hand, Fitzpatrick and Rose (1936) report larger numbers of wheat roots in the $B_2$ horizon than in the $A_2$ horizon of Oswego silt loam. This soil approaches a Planosol in its characteristics, but the $B_2$ horizon is less dense and tight than is characteristic of most claypans. Stephenson and Schuster (1937) found that Persian walnut trees sent roots down 10 ft. or more in soils with good aeration. There were few roots below a depth of 4 ft., however, in soils with poor aeration because of fine-textured deeper layers. These authors also mention the limitations in growing deep-rooted crops on Dayton soils in eastern Oregon because of the claypan subsoil.

*(3) Clay minerals and fertility status.* The high plasticity of claypan horizons and layers is a good index of the nature of clay minerals in them. Studies of the B horizons of Planosol and Solonetz soils indicate that 2:1 lattice type minerals predominate though 1:1 lattice type minerals are present in small quantities (Clark, Riecken, and Reynolds, 1937; Bray, 1937; Whiteside and Marshall, 1944; Brown and Caldwell, 1946; Larson, Allaway, and Rhoades, 1946; Cady, 1950). Illite and montmorillonite groups are both represented, with the latter commonly more plentiful. Claypan subsoils other than B horizons also seem to contain clay minerals mainly of the 2:1 lattice type. These minerals have been identified as major ones in the deeper layers of the Susquehanna,

Vaiden, Leaf, and related series (Kelley *et al.*, 1939; Pearson and Ensminger, 1948; Dyal, Martin, and Templin, 1950). The predominance of 2:1 lattice type minerals is reflected in high base exchange capacities as well as in plasticity.

The base exchange capacities are high in most claypans. Ranges in base exchange capacities are commonly from 25 to 50 me. per 100 grams soil, but occasionally may be as low as 20 me. and more often as high as 70 me.

In the B horizons of Planosols, base saturation ranges downward from 100 per cent in soils associated with the Chernozems to about one-fourth of that value in soils associated with Gray-Brown Podzolic soils. In the fine-textured subsoils which function as claypans but are not genetic horizons, the quantities of exchangeable calcium, magnesium, potassium, and sodium are often very low while that of hydrogen is high. Not all nongenetic claypans are strongly acid. The exchangeable cations are dominantly calcium and magnesium in the B horizons of Planosols associated with Prairie and Chernozem soils, with hydrogen, potassium, and sodium present in minor amounts. Exchangeable calcium and magnesium are also more plentiful in the B horizons of most Solonetz soils although sodium is prominent in many of them (Rost, 1936; Smith, 1937; MacGregor and Wyatt, 1945; Riecken and Stalwick, 1945). Solonetz B horizons are at times very high in exchangeable magnesium and relatively low in exchangeable sodium. Rost (1936) describes soils in which the B horizons contain 50 me. magnesium, 19 me. calcium, and 1 me. sodium per 100 grams soil. Because Solonetz B horizons do have high base saturation, they are more alkaline in reaction than the claypans of Planosols or the nongenetic claypans.

A few analyses for organic matter and nitrogen (Brown, Rice, and Byers, 1933; Kellogg, 1934; Smith and Rhoades, 1942a; Ulrich, 1949) indicate that contents are about the same in the claypans as in the B horizons of associated zonal soils. By and large, the amounts are low. Planosols such as Edina silt loam (Ulrich, 1949), and Cowden silt loam (Whiteside, 1944) have B horizons slightly higher in organic matter than the overlying $A_2$ horizons.

Total quantities of nutrients and quantities of available phosphorus in claypans are of the same order of magnitude as those of zonal soils and stand in the same relationship to the amounts in the adjacent A and C horizons. Fertility status of claypans, however, is not a primary limiting factor in plant growth. The problems which beset efforts to grow plants on soils with claypans are primarily those caused by unfavorable physical subsoil properties. Where such subsoils are exposed by erosion, tillage becomes very difficult.

*b. Fragipans.* The term "fragipan" refers to a horizon in the profile that is very slowly permeable, compact or dense, hard when dry, and moderately friable to friable when moist. These layers have most often been called "siltpans" in the past, but some are distinctly sandy rather than silty. They have also been called "brittle pans." The horizons were called "silica pans" by Winters (1942) to indicate the probable cementing agent. The fragipans received little attention prior to the last decade, and there are but few studies of their general character and significance.

*(1) Distribution.* Soils with fragipans have been considered Planosols in recent years. The presence of a pan within the profile is an outstanding feature which is emphasized by that classification. Soils with fragipans are widely distributed in humid-temperate regions. They have been observed and described especially in the Red-Yellow Podzolic regions (Fig. 2) of the United States (Winters, 1942). They are common in those portions of the Gray-Brown Podzolic region which border the Red-Yellow Podzolic soils and interfinger with them. Soils with fragipans also seem to be associated with podzolic soils in the northern United States and Canada. Stobbe (1937) mentions the occurrence of a "hardpan" thought to be cemented with silica in certain poorly drained soils associated with Gray-Brown Podzolic types in the Appalachian foothills of Quebec. Kellogg (1930) also describes a compact and brittle layer in the Mason soils associated with Podzols in northern Wisconsin. These soils are thought to be identical with the Munising series, described in Iron River County, Michigan, as having a compact or cemented subsoil layer (Foster, Veatch, and Schoenmann, 1937). These compact or cemented and brittle layers in subsoils in the Podzol region seem to be essentially similar to the fragipans in the Red-Yellow Podzolic zone.

The Planosols with fragipans are generally developed from medium-textured parent materials. They are especially widespread among the soils formed from loess in the lower Mississippi Valley. They are also prominent components of the pattern among soils formed from shallow loess overlying various types of materials in this same section. Soils with fragipans are also present in regions of the southern United States where the parent materials include no loess component. They have been observed in soils formed from crystalline rocks, from various sedimentary rocks, and from various unconsolidated sediments. So far as is known, however, the pans are present only in soils formed from medium-textured materials. The distribution of Planosols with fragipans outside of North America is unknown, but it seems reasonable that they must occur in other parts of the world.

*(2) General characteristics.* Fragipans are commonly very hard when dry, friable when moist, of intermediate texture, and of high volume weight. Even so, fragipans are seldom sharply differentiated from adjacent horizons. Furthermore, they exist in all degrees of development from faint ones which are barely evident under favorable moisture conditions to prominent ones which seem completely indurated when dry.

Fragipans usually occur well down in the soil profile and have a considerable range in thickness. They are usually found at greater depths than the claypans in Planosols or the B horizons in zonal soils. Except on very level topography, fragipans commonly lie 20 to 30 in. below the surface of the soil. On very level areas, the top of the pan may be within 15 in. of the surface. Commonly the more distinct pans are nearer the surface, and the less distinct pans are deeper in the profile. Grenada silt loam in Marshall County, Kentucky, has a distinct pan which begins at a depth of about 24 in. and extends downward for some 20 to 24 in. (Leighty and Wyatt, 1950). In the associated Loring silt loam, there is some evidence of incipient pan formation between depths of 32 and 42 in. (Leighty and Wyatt, 1950). The pan in Leonardtown silt loam begins at depths of 20 to 24 in. (Nikiforoff, Humbert, and Cady, 1948).

Occasionally, a pronounced clay accumulation is associated with a fragipan. It is not clear whether the clay accumulation represents part of a buried soil formed in a previous cycle or a soil horizon formed in the current cycle of soil development. The presence of the clay accumulation is but one among the unexplained features of fragipans. More investigations are needed to develop satisfactory theories for the genesis of the pans and to devise ways of utilizing effectively the soils in which they occur.

Fragipans are commonly medium-textured with silt loam as the predominant texture class (Winters, 1942; Smith and Browning, 1946a; Nikiforoff, Humbert, and Cady, 1948; Leighty and Wyatt, 1950). Although silt loam is the most common texture, very fine sandy loam and silty clay loam are also widespread. Fine sandy loam, clay loam, and sandy clay loam textures are less common but have been reported. Because of lower contents of clay, the fragipans are much less plastic than are claypans. By and large, they are slightly plastic when wet. Most of them are hard when dry but crush suddenly and completely under severe pressure.

Volume weights are generally much higher in fragipans than in overlying horizons. For example, the maximum value reported by Nikiforoff, Humbert, and Cady (1948) for the pan in Leonardtown silt loam was

1.87 as compared with a value of 1.47 in the A horizon. Recently obtained unpublished data on the fragipan in Grenada silt loam in western Tennessee and Kentucky are slightly lower, ranging near 1.6. These values, however, are higher than those of associated A and B horizons. With the high volume weight and associated low porosity, it is to be expected that permeability will be very low. Unpublished data on the soils in western Tennessee and Kentucky indicate percolation rates as low as 0.02 in. of water per hour through 3-in. cores taken from fragipan layers. Observations of moisture movement into the pan of Leonardtown silt loam over a three-month period also indicate very low permeabilities (Nikiforoff, Humbert, and Cady, 1948). The implications of the low permeabilities are obvious when compared with percolation rates of 2.98 in. per hour through 3-in. cores of the A horizon from Grenada silt loam.

Levels of plant nutrients seem to be low in fragipans although the data are extremely limited. The pans have low pH values and correspondingly low base saturation as a general rule (Smith and Browning, 1946a). The amounts of nitrogen and available phosphorus also seem to be extremely low. Total quantities of calcium, magnesium, potassium, and phosphorus in the pans, on the other hand, are similar to those in other subsoil layers. The low fertility levels are much less important than the unfavorable physical properties.

Change in consistence with change in moisture content is a striking feature of fragipans. Even the more pronounced pans are usually moderately friable when moist, and a soil auger will pass through the pan easily. Under favorable moisture conditions, a distinct fragipan may simply appear as a mottled horizon in the profile. On the other hand, the pans become very hard when dry and a soil auger frequently fails to penetrate. Exposures of pans in road cuts become hard enough so that a spade blade struck against the exposure will ring. Along secondary roads, outcrops of distinct fragipans appear as "knees" in the cuts (Marbut, 1935).

It has been noted that a lump of soil from a fragipan horizon will slake down and crumble if placed in water after air-drying. The tendency of pan fragments to crumble and lose their form suggests that pans would not re-form if broken up by tillage or other means and allowed to dry.

The slaking of lumps from fragipan horizons has been considered evidence that the layers were not cemented by silica as proposed by Stobbe (1937) and Winters (1942). It is true, however, that the pans occur generally in regions where release of large quantities of colloidal silica can be expected through the weathering of either primary or secondary silicate minerals. Tamm (1932) reports large quantities of colloidal silica in drainage waters from Podzols in Sweden. Similarly, the mineral composition of clay fractions in Red-Yellow Podzolic soils studied by Pearson and Ensminger (1948) suggests that appreciable quantities of kaolinite in the upper solum have broken down through hydrolysis. The possibility of silica functioning as a cementing agent is not accepted by Nikiforoff, Humbert, and Cady (1948). Nevertheless, it does seem necessary to postulate some cementing agent to explain the changeable hardness of fragipan horizons. If the cement were silica gel, drying would destroy its cementing power and permit subsequent slaking of the soil in water. The silica gel would not regain its cementing properties unless it were redissolved and reprecipitated, which would not occur as the soil was rewetted with water. Regardless of the nature of the cementing agent or the origin of the pans, however, they do interfere with plant growth and pose special management problems over considerable areas.

*c. Hardpans.* As used here, the term "hardpan" refers to horizons and layers with definite cementation. Hardpans are clearly indurated, as a rule, but there are all gradations from the fragipans and claypans, on the one hand, to the strongly cemented ones, on the other. The intent here is to restrict hardpans to layers that cannot be broken easily with the hands whether they be wet or dry.

Several types of hardpans, differing in origin, are known to exist. In most of the pans, iron oxide, silica, organic matter, or calcium carbonate, either singly or in combination, are the cementing agents. Two well-known types of hardpans are the ortstein B horizons of Ground-Water Podzols (Baldwin, Kellogg, and Thorp, 1938) and the laterite crusts associated with Ground-Water Laterites (Marbut, 1930; Thorp and Baldwin, 1940). Less well known and probably less extensive are the iron-silica hardpans in soils such as the San Joaquin series in California (Nikiforoff, 1941). Striking and fairly extensive hardpans in some dry regions are cemented layers high in calcium carbonate, known as caliche or croute calcaire (Breazeale and Smith, 1930; Aubert, 1947). Caliche layers are discussed with other hardpans even though there are a number of important differences in properties. All the hardpans have a high degree of cementation and distinct hardness as definitive features.

*(1) Ortsteins.* The term "ortstein" refers to the B horizon of Ground-Water Podzols and is derived from two German words meaning "stone in place." Examples of Ground-Water Podzols are Saugatuck sand in the northern and Leon sand in the southern United States. These soils occur in association with Podzols (Lyford, 1938), with Red-Yellow Podzolic soils (Hearn, 1931), and Latosols (Roberts, 1942).

Ground-Water Podzols are widely distributed in northern Europe and Asia (Rathlef, 1930) and in tropical and subtropical regions (Thorp and Baldwin, 1940). Available detailed soil maps, however, do not indicate that Ground-Water Podzols are of major extent in many places. They seem to occur as characteristic minor parts of the soil pattern.

The ortstein or B horizon of Ground-Water Podzols is commonly thin, either is hard in place or becomes hard upon exposure to air, and is high in iron oxides, organic matter, or both. The ortsteins in the northern United States (Lyford, 1938) as well as those in Europe (Rathlef, 1930) commonly resemble conglomerate or concrete in general structure, with the coarse particles cemented together by iron oxides to form the hardpan layer. Ortstein normally occurs in coarse-textured soil material such as sands, coarse sands, gravels, or mixtures of these. It is seldom found in medium to fine-textured soils. Cementation of the ortstein horizon normally is discontinuous throughout individual areas of Ground-Water Podzols.

Ground-Water Podzols of the southeastern United States and of tropical regions are formed in sandy, acid sediments with organic matter as the major cementing agent in the B horizon or hardpan (Hearn, 1931; Roberts, 1942; Thorp and Baldwin, 1940). This group of soils can be illustrated by the Leon series which has a dark B horizon, usually a few inches thick, occurring at depths of 15 to 24 in. (Hearn, 1931). This B horizon, sometimes called an "organic pan," is seldom hard enough in place to stop a soil auger. It does seem to harden irreversibly upon drying and exposure to air; where the organic pan is exposed in a road cut, it is normally hard.

In Leon soils, the organic pan appears to be a B horizon both in its position within the profile and in its relationships to other horizons. It is true, however, that organic pans occur at all depths from 15 in. to 25 ft. and that several may occur in a single vertical section. Consequently, there is some question about the interpretation of the organic pan as the B horizon. Various hypotheses have been offered to explain the origin of the organic pan and of multiple pans within a profile, but their genesis still remains obscure. Regardless of the origin of these pans, however, they are significant to plant growth when they occur at shallow to moderate depths in the profile.

*(2) Laterite crusts.* The place of laterite crusts in a discussion of hardpans may be subject to question. As described by various investigators laterite may exist as a concretionary layer or as a continuous crust (Thorp and Baldwin, 1940; Pendleton and Sharasuvana, 1946; du Preez, 1949; Aubert, 1949; Sherman, 1950; Kellogg, 1950). It may be strongly indurated or it may harden upon exposure. Furthermore,

hard crusts occur both at and below the surface. Many of these observations raise a question about the proper place of laterite crusts or laterite generally in a discussion of hardpans. In contrast to these observations, the available evidence supports the view that laterite crusts form within the profile (Marbut, 1930; Thorp and Baldwin, 1940; du Preez, 1949; Kellogg, 1950). Moreover, the soil horizons that do harden into crusts upon exposure normally exist as a part of the subsoil if they are within the soil profile (Kellogg and Davol, 1949). Consequently, laterite crusts are discussed as hardpans although the authors do recognize that many laterites are not strongly indurated, that some laterites exist as concretionary layers, and that some crusts are now at the surface.

Ground-Water Laterites with iron crusts in the deeper profiles or with subsoils that harden irreversibly upon drying are widely distributed in tropical regions (Marbut, 1930; Thorp and Baldwin, 1940; Pendleton and Sharasuvana, 1946; Stephens, 1946; Aubert, 1949; du Preez, 1949; Kellogg and Davol, 1949; Sherman, 1950). Aside from the iron crusts within the profile as described by Marbut (1930), the laterite crusts or hardpans cover important areas of old land surfaces in the tropical portions of Africa, Asia, and South America. Very extensive areas of laterite crusts formed in an earlier geologic epoch are now present in the land surface in parts of Australia (Stephens, 1946). Somewhat similar crusts, commonly called ironstone layers, exist in the deeper profiles of Red-Yellow Podzolic and associated well-drained soils of the United States. Among the various kinds of hardpans, laterite crusts seem to be by far the most extensive and hence are most important in their relationships to plant growth.

Descriptions of two types of laterite crusts and of a concretionary laterite should serve to illustrate the property ranges that do exist. Hard slag-like masses which seem to be continuous over considerable areas have been described in Australia by Stephens (1946) and in Siam by Pendleton and Sharasuvana (1946). These crusts consist of sesquioxides, dominantly iron oxides, with appreciable quantities of entrapped quartz and other resistant minerals. The massive layers are identical in chemical composition or nearly so with the laterite used in the construction of temples in southeastern Asia (Pendleton and Sharasuvana, 1946). Thickness of the crusts is variable but seems to be a matter of feet rather than inches. Laterite crusts of this type are thought to have been formed by hardening of an illuvial horizon after it is exposed by erosion (Thorp and Baldwin, 1940; Pendleton and Sharasuvana, 1946; Aubert, 1949). Necessary conditions for the formation of these crusts are described by Thorp and Baldwin (1940), du Preez (1949), and Kellogg (1950).

A less indurated type of laterite crust has been studied by Sherman (1950) in Hawaii. This crust, though not strongly indurated, is still relatively hard and will not support plant growth. It resembles the fragipans in its high initial resistance to crushing and also in that it crushes to graphite-like powder once it gives way. Thickness of the laterite crusts in Hawaii is commonly less than a foot, and Sherman (1950), who postulates the formation of the crusts through lateral movement of ground waters, calls attention to their relative instability in a landscape undergoing active dissection. Although dominated by iron and titanium oxides, the crusts are not strongly cemented and tend to collapse readily when undercut. Aubert (1949) describes similar undercutting followed by collapse and partial removal of crusts in Africa. The distinctions between the crusts in Hawaii and the massive laterite crusts of Australia, Asia, and Africa seem to be in thickness and in degree of induration rather than in composition. Both crusts consist largely of sesquioxides and are essentially sterile, as far as plants are concerned.

A third type of laterite, comprising a concretionary horizon, has been described in Africa (du Preez, 1949; Dubois, 1949), in Puerto Rico (Roberts, 1933), and in the Palau Islands (Bridge and Goldich, 1948). These concretionary layers may occur directly on the surface, in which case they support very poor plant growth. Dubois (1949) suggests that they represent extreme weathering of the soil. The accumulation of concretions was also thought to indicate a high degree of weathering by Craig and Halais (1934) who found that the numbers in soil formed from doleritic basalt in Mauritius increased with increasing rainfall. Other indications of more intense weathering accompanied the larger numbers of concretions. Concretionary layers differ from continuous laterite crusts in that they do not interfere as much with water and root penetration. Moisture relations are poor, however, because of the small amounts of silt and clay commonly present in the concretionary layers. At the same time, these layers are strongly weathered and seem to have a fertility status as low as that of indurated crusts.

The hardpan layers of soils in humid regions are generally acid, low in fertility, and high in their capacity to fix phosphorus. Thus, even when hardpans are broken up or shattered, the resulting material usually offers a very poor medium for plant growth. Furthermore, the medium is not readily improved by fertilization or other management practices. There are occasional reports (Chevalier, 1949) that laterite crusts will, in some instances, disappear under forest cover within a few decades. By and large, however, it seems that hardpans are poor for plant growth whether broken up or left intact. Undisturbed soils with distinct hardpans are commonly poor both for the natural vegetation and for crops.

*(3) Iron-silica hardpans of dry regions.* So far as is known to the authors, this type of hardpan is restricted to regions of desertic soils (Fig. 1). These pans have not been studied widely though they have been described rather completely in the San Joaquin soils of California (Bodman, 1931; Nikiforoff, 1941; Nikiforoff and Alexander, 1942). Hardpans of this or related types occur widely in Desert soils, according to Nikiforoff (1937).

The depth to and thickness of the hardpan in the San Joaquin soils has been studied carefully by Nikiforoff (1941). The upper surface of the pan, which is commonly a sharp boundary, lies 1 to 2 ft. below the present soil surface. Nikiforoff (1941) found little relationship between the upper surface of the hardpan and the present land surface. Thickness of the hardpan varies between 2 to 3 ft. as a rule, but may be as much as 4 ft. Because there is a gradual change in properties with depth, the lower boundary of the hardpan cannot be identified precisely.

There are considerable differences in physical properties within the hardpan. The upper part is strongly indurated and almost comparable to stone in places (Nikiforoff, 1941). On the other hand, the lower part of the pan is much less hard and seems to have some of the characteristics of fragipans. Maximum volume weights, as reported by Bodman (1931), are near 2.0, slightly higher than those of the fragipan in Leonardtown silt loam, ordinarily considered very dense and compact. With the high volume weight in the San Joaquin hardpan, there is a correspondingly low porosity. Bodman (1931) found that pore space was about 25 per cent in the hardpan as compared with approximately 40 per cent in the $A_1$ horizon. The hardpan in San Joaquin soils seems to be impervious to water and plant roots.

Cementing materials in the hardpans are chiefly silica and iron oxides (Nikiforoff and Alexander, 1942), although carbonates were observed in the deeper part of the pan in some profiles. The hardpans are commonly alkaline in reaction and may be lower in clay than other horizons but seem to be similar in chemical composition to the other horizons of the profile. The distinctive features are the physical characteristics.

Like the other types of hardpans, the iron-silica pan is generally not favorable for plant growth even after it has been shattered. The San Joaquin hardpan is not acid, but its unfavorable physical properties are marked enough to make chemical composition of limited importance.

*(4) Caliche.* The term "caliche" is used here to refer to layers cemented by calcium carbonate in and below soil profiles of arid and semiarid regions. The indurated layers are also known as "croute

calcaire'' and the name ''calcipan'' has been suggested for them. They vary in composition, thickness, and degree of induration. They are all high in calcium carbonate, however, and are all alkaline in reaction. Caliche is widely distributed in the warmer portions of desertic zones, shown in Fig. 1, which include the regions of Sierozems, Red Desert, Brown and Reddish Brown soils of the southwestern United States (Fig. 2). They have not been reported in chernozemic, podzolic, or latosolic zones. (Breazeale and Smith, 1930; Youngs *et al.*, 1936; Harper and Smith, 1932; Denny, 1941; Aubert, 1947)

Caliche varies widely both in thickness and hardness. The layers may be only a few inches thick, or they may be many feet in thickness (Breazeale and Smith, 1930; Youngs *et al.*, 1936). Strongly indurated layers are commonly, but not always, thicker. Breazeale and Smith (1930) describe thick caliche beds in which there are numerous thin dense layers of nearly pure calcium carbonate sandwiched between layers of gravel and sand. These authors also describe caliche layers which are soft in place but become putty-like and can be molded when wet and which harden upon exposure. The Casa Grande ruins near Florence, Arizona, were built from caliche of this type which is still in a fair state of preservation (Breazeale and Smith, 1930). Caliche which has attracted the most attention, however, is the indurated form existing as crusts either below or at the surface.

Caliche may occur within or below the soil profile, or it may be exposed on the land surface. The depth to caliche layers ranges from inches in some soils to many feet in others. Harper and Smith (1932) describe large areas in which the caliche hardpan is partially exposed and is otherwise covered by a thin layer of windblown sediments. In addition to the variations in depth of overlying soil materials, there may be a succession of caliche pans within a single vertical cut somewhat like the occurrence of multiple organic hardpans in Ground-Water Podzols of the southeastern United States (Breazeale and Smith, 1930). The location of caliche with respect to the A and B horizons of the soil seems to depend upon rainfall, evaporation, amounts of run-off, composition of soil material, and position in the landscape. As indicated by Breazeale and Smith (1930), the various types of caliche may be formed under a number of different conditions. No uniformity of origin is suggested by these authors except that all caliche is formed by precipitation of carbonates.

Except for the fact that caliche is all highly calcareous and alkaline, there seems to be little uniformity of composition. Some caliche approaches the purity of calcite, whereas other layers are essentially calcareous conglomerates. Breazeale and Smith (1930) report that the strongly cemented layers are generally low in magnesium carbonate, but that soil associated with these layers is frequently high in magnesium. On the whole, caliche layers can be expected to be very high in calcium, medium to high in magnesium, medium to low in potassium, and low to very low in organic matter, nitrogen, and available phosphorus.

With the wide ranges in composition, in thickness, in hardness, and in mode of origin, it is to be expected that the occurrence and distribution will also be variable. In some soils, the caliche is fragmental and resembles stones or coarse gravel in the deeper profile. In other soils the caliche may be massive and occur in spots which are measurable in square feet. Some of the massive caliche, however, seems to cover large areas, as for example, the scabland in Lea County, New Mexico (Harper and Smith, 1932). Breazeale and Smith (1930) also report large areas of soils underlain by massive caliche.

Massive caliche layers which lie near the surface or within the profile are a serious hindrance to water and root penetration. If, however, the caliche is fragmental or weakly cemented, it has little mechanical effect upon either water or root penetration. In most cases, the highly calcareous layer is deficient in nutrient elements such as phosphorus, iron, and boron. Even so, caliche pans contain larger amounts of plant nutrients than do other types of hardpans. Many of the soils with caliche layers are useful for shallow-rooted plants or for plants which can adapt themselves to shallow rooting zones. Where massive caliche layers lie near the surface, however, the soils are of limited usefulness for plant growth.

*(5) Other hardpans.* In addition to the types of hardpans discussed thus far, there are at least two more kinds, and there may be others. The Roane soils found in poorly drained flood plains in eastern Tennessee, have cherty subsoils which constitute hardpans in places (Hubbard, Matzek, and Jenkins, 1948). The pan is formed of interlocking chert pieces mostly of coarse gravel size which are slightly cemented by iron and manganese oxides. The Roane series also occurs in the Ozark regions of Arkansas and Missouri, but the total acreage is small. Nikiforoff (1937), in discussing general trends of soil formation in deserts, calls attention to the widespread occurrence of ''hardpans'' or crusts. He states that the most common crusts are of the lime and gypsum type and the lime-silicic type. He also states that strongly indurated pans cemented only by soluble silica almost certainly occur. These hardpans are somewhat different from those discussed in other parts of this section on pans. The occurrence of ''chert pans'' and indurated silica pans does suggest the possible existence of types of hardpans which as yet have received little attention.

### 3. *C and D Horizons*

As indicated earlier in the paper, the C horizon is usually defined as a layer of unconsolidated and partly weathered geological material relatively unchanged by soil-forming processes. The D horizon is any unconforming material below the C horizon or, if the C horizon is absent, below the A or B horizon. The boundary between the C and overlying A or B horizon is gradational rather than sharp, and the upper boundary of the C horizon can therefore not be placed with precision. Occasionally, there is a sharp break between an A or B horizon and an underlying D horizon markedly different in physical and mineralogical composition. The C or D horizon is a part of the profile of every great soil group. It is universally present wherever soils have been formed, though the depth to the C horizon may be so great that the properties of the C horizon have little significance to ordinary crops.

*a. Depth to C and D Horizons.* The range in depth to the C horizon extends from a matter of inches in Regosols to a matter of many feet in deeply weathered Latosols. For that matter, young Alluvial soils may consist entirely of C horizon without an A or B horizon. Considering the broad soil groups for which B horizons were discussed under Section III 1, the latosolic soils are deep enough so that the C and D horizons are beyond reach of the roots of many plants. They are probably reached by some deep-rooted trees. Among the podzolic soils, the C or D horizon is much nearer the surface and lies within the rooting zones of many common crops. This is also true for soils of the chernozemic and desertic zones generally. For example, in some Podzols, Brown Podzolic soils, and Brown soils, the major part or even all the A and B horizons may be included in the furrow slice. The character of the C or D horizon or both then becomes important to the success or failure of crop production. The nature of the C or D horizon is also important when the overlying horizons are removed by accelerated erosion.

*b. Ranges in Properties.* The nature of any C horizon depends upon the local geology and climate because this horizon lies below the effective reach of biological forces that operate in the development of A and B horizons. For example, certain processes function in the genesis of all Podzols or of all Chernozems. As a result, the A and B horizons of all Podzols or of all Chernozems tend to have similar color, structure, and reaction, to name but a few characteristics. These processes of soil genesis have little effect upon the C horizon and, as a consequence, there is much more variability among C horizons of a great soil group. This statement applies with equal force to D horizons, which constitute materials markedly different from those of the A and B horizons.

To illustrate the local ranges possible in properties of C horizons, examples from Illinois, Kentucky, North Dakota, and Iowa have been chosen. Winters and Wascher (1935) found textures ranging from sand to clay in a study of glacial till in northern Illinois. The samples were all taken from a single till sheet within a limited area. Similarly, the differences in C horizons among the soils of Marshall County, Kentucky, reflect the geological history of the area (Leighty and Wyatt, 1950). For example, some C horizons consist of loess, some of marine sediments, and some are residual from cherty limestones. In the same county, many soils have D horizons consisting of marine gravels or chert beds with overlying A and B horizons formed largely from loess. Comparable variety exists among the C horizons in McKenzie County, North Dakota, where the parent materials include sandy glacial till, loamy glacial till, clayey glacial till, gravelly outwash, scoria, and unconsolidated sedimentary sands, silts, and clays (Edwards and Ableiter, 1942). Among the drift sheets in Iowa, the depth of leaching of carbonates is a reflection of age where the drifts are of similar composition and have comparable geomorphological histories. Average depth to carbonates in Mankato till of intermediate texture on gently undulating, well-drained upland sites is about 30 in. The comparable depth in the Iowan till under similar circumstances is about 50 in. Thus, in the one case, the C horizon is calcareous and in the other it is not.

Because the properties of the C horizon do depend upon the nature of the parent rock and upon the geological history, the ranges in all characteristics are extremely wide. C horizons may be acid or alkaline, low or high in plant nutrients, highly siliceous or very low in silica—to cite but a few characteristics. Comparable ranges can be expected in all properties of C horizons (Hearn, 1931; Winters and Wascher, 1935; Roberts, 1942; Sherman, 1949; Oakes and Thorp, 1950).

The ranges in properties of D horizons are wider than those of C horizons. The occurrence of many soils with D horizons in Marshall County, Kentucky, has already been mentioned (Leighty and Wyatt, 1950). These are examples of the large aggregate acreage of soils in the Mississippi Valley that have A and B horizons formed from loess overlying a D horizon of unrelated geological material. The loess feathers out over glacial drift, marine sediments, and residuum from various kinds of limestones, sandstones, and shales. Soil profiles which are marked by an unconformity in geological materials are widely distributed in the Great Plains as well as in the Mississippi Valley. They may be more extensive than is realized in the Coastal Plain of the southeastern United States, and they must also occur widely in other parts of the world blanketed by loess or alluvium. In such soils, there is frequently a sharp break in properties in passing from the A or B horizon to the D horizon. Jenny (1941) has pointed out the importance of considering such unconformities in genetic interpretations of soil profiles. These unconformities must be recognized if the proper interpretations of soil genesis are to be made. Furthermore, the sharp breaks in properties have much significance to plant growth.

*c. Significance of Properties.* Readily observable properties that serve as indexes to more basic characteristics of soils may not have the same significance in the C and D horizons as in the B horizon. For example, color is widely used in the study of B horizons as a guide to the degree of aeration and drainage under natural conditions. Oftentimes, also, it is used as an aid in evaluating permeability. Color is a far less satisfactory guide to aeration and drainage of C and D horizons. The yellow and red colors usually associated with moderate to good drainage and aeration in the upper B horizon do not necessarily mean the same things in C or D horizons. These colors may persist in the deeper subsoil where other evidence clearly indicates poor drainage with considerable waterlogging and consequent poor aeration. Organic matter and biologic agents, which Albrecht (1941) has found important in reducing iron compounds in soils, are so limited as to make it possible for red and yellow colors to persist in C and D horizons with very poor drainage and aeration.

It is far more difficult to generalize about the properties of C or D horizons than about the properties of B horizons or pans. Fewer generalizations are possible on a broad scale. For definite predictions of C or D horizon properties, soil groups must be at least as low in category as the series level. On the other hand, generalizations about the B horizon are oftentimes valid at the level of abstraction of the great soil group and certainly at that of the family category. The C and D horizons, however, are important to plant growth in certain soils. In so far as plants are concerned, they are part of the subsoil in many instances and thus require consideration and study along with B horizons and pan layers, even though fewer generalizations can be made about them as a group.

### 4. *Temperature Regimes*

Subsoil temperature is more changeable than characteristics such as texture, permeability, clay mineral composition, and fertility status, which have been given major attention in this paper. Temperature differs from other soil properties except moisture content in that it may fluctuate from day to day and from season to season. Partly because of this, subsoil temperatures do not lend themselves well to discussion on the basis of B horizons, C and D horizons, and pans. Nevertheless, subsoil temperature does affect the behavior and functioning of roots and may have an important bearing on plant growth. A brief discussion of temperature regimes in subsoils therefore seems desirable.

Soil temperature may vary with profile depth, with the time of day, and with the seasons. The absolute temperatures of the surface soil and subsoil at any given time usually differ, and there are also differences in the magnitude and frequency of fluctuations in the two. By and large, the diurnal and seasonal changes in temperatures are smaller in subsoils than in surface soils.

Where marked daily fluctuations occur in atmospheric temperatures, there are usually fluctuations in soil temperatures as well. In extreme cases, the daily temperature fluctuation may be as great as 100°F. in the topmost quarter-inch layer of dry surface soil, but diurnal ranges never approach this in the subsoil. Turnage (1939) found that daily fluctuations were not detectable at depths of 3 ft. or more, and the data of Taylor (1928) are in essential agreement with this finding. Kandasamy (1937) reports that daily temperature fluctuations did not occur below a depth of about 2 ft. under tropical conditions. Consequently, daily changes in temperature may occur in some B horizons but seldom extend into the C or D horizons. They also occur in some pan layers.

Although daily fluctuations in temperature do not extend into the subsoil, the seasonal variations may continue downward for several feet. Thomson (1935) found a seasonal variation of 4°F. at a depth of 15 ft. under chernozemic soils at Winnipeg, Canada. Within the soil profile itself, the seasonal variations were as large as 35°F. at 1 ft. and 33°F. at 20 in. A depth of 20 in. lies within the B horizon or possibly in the upper C horizon of soils in that region. Thomson (1935) reports average temperatures of 27°F. in March and 60°F. in October at a depth of 20 in. Even at a depth of 11 ft. the temperature was 36°F. in April as compared with 48°F. in October. These records extended over a three-year period. Smaller seasonal variations have been reported at Davis, California, by Smith (1932). The differences between maximum and minimum temperatures at a depth of 3 ft. were 25°F., and those at a depth of 12 ft. in the same profile were about 7°F. Even smaller seasonal variations in temperature are to be expected in latosolic soils where there is little change in the average atmospheric temperatures from one season to another. The maximum seasonal variations in subsoil temperature can be expected in Chernozems and related soils of the middle latitudes.

In cool-temperate and frigid zones where winter temperatures fall below the freezing point every year, the soil freezes to some depth. This depth varies from a matter of feet in the tundra, podzolic, and chernozemic soils of high latitudes to a matter of inches in Gray-Brown Podzolic soils of middle latitudes (Fig. 1). In the United States, for example, available evidence suggests that the A but not the B horizons of Gray-Brown Podzolic soils are frozen in a majority of winters (Post and Dreibelbis, 1942). It seems possible that maximum frost penetration will not extend through the A horizon in some winter seasons, whereas it may reach into the C horizon in others. At Winnipeg, Canada, on the other hand, Thomson (1935) found that the average temperature during the month of March was at or below the freezing point to a depth of 5 ft. This is commonly below the C horizon of Chernozems in North America. At depths which normally lie in the B or upper C horizons of Chernozems near Winnipeg, the average temperature in March was 5° below the freezing point. Similar relationships can be expected generally in the middle and high latitudes where air temperatures fall below freezing for considerable periods every winter season. These conditions do not extend into low latitudes except at high elevations. Taking another example from the United States, the frost line does not extend much below Tennessee and Oklahoma.

Depth of frost penetration is greatest in high latitudes, other things being equal. It also seems to be greatest where there is less cover as for example, in the Chernozem and Chestnut soil zones where snowfall is not heavy and where the ground cover is grass or residues from grain crops. Referring to the broad belts of soils outlined in Fig. 1, it can be said that podzolic soils are generally subject to freezing, at least in the upper B horizons. Furthermore, the C horizon as well as the B horizon commonly freezes in Podzols and related soils of higher latitudes. On the other hand, no part of the subsoil is ever frozen in latosolic soils. Among the chernozemic and desertic soils, those in high and middle latitudes freeze down through the C horizon whereas those of low latitudes are not subject to freezing. In the United States, for example, freezing extends into the B and C horizons in the Podzol, Chernozem, Chestnut, and Brown soils. It occasionally extends through the B horizons and into the C horizon of soils in the Gray-Brown Podzolic zone. On the whole, however, frost action will only be significant in the deeper horizons of soils that lie in higher latitudes than Gray-Brown Podzolic soils.

The Tundra soils with permafrost layers were mentioned briefly in an earlier discussion of the B horizons of podzolic soils. The regions of Tundra soils (Fig. 1) include the areas with perpetually frozen subsoils. Not all soils in these broad regions, which extend around the earth near the poles, have a permafrost layer as part of the profile. The distribution of permafrost and of intermittent permafrost layers is shown for

Alaska by Kellogg and Nygard (1951). The perpetually frozen subsoils in Siberia have been discussed by Nikiforoff (1928), and those of northern Canada are mentioned by Feustel, Dutilly, and Anderson (1939). The permafrost layer is not accessible to plant roots and forms a barrier to moisture movement. There is no opportunity for drainage and removal of water through the soil itself. Moreover, the network of surface drainageways is commonly poor in the tundra region, and there is little opportunity for removal of water by run-off. As a consequence, these soils tend to remain wet during the summer months, even after the upper horizons are no longer frozen. During the winter months the soil again freezes down to the permafrost layer.

For many of the soils in which useful plants are grown, subsoil temperatures at moderate depths tend to remain fairly uniform throughout the growing season. Where changes do occur, as in Chernozems, the subsoils become warmer as the summer season progresses. There are generally considerable time lags, however, between the occurrence of the maximum atmospheric and maximum subsoil temperatures. For example, the maximum subsoil temperature at Winnipeg, Canada, occurs in October (Thomson, 1935), whereas the maximum air temperatures arrive during July and August. Even so, subsoil temperatures are generally below surface soil and atmospheric temperatures during most of the growing season. The effects of lower temperatures in subsoils as compared with surface soils are of more importance to trees and other plants with many deep roots than to grasses and similar plants with a great majority of roots in the uppermost horizons.

### 5. *Variations in Nature and Properties*

To simplify discussion, subsoils have been considered chiefly in terms of B horizons, C and D horizons, and various types of pans. Major characteristics of these different kinds of subsoil layers have been sketched briefly. Attention has been given only to the major features in an effort to deal with subsoils generally. Even with this limitation on the discussion, however, it is clear that a wide variety of subsoils exist and that few generalizations will be valid for all.

In the first place, B horizons and pans, when present in the profile, lie nearer the surface than do the C and D horizons and thus have more effect on water movement, root penetration, and plant nutrition. In the second place, as a rule, the properties of B horizons and pans are more strongly expressed than those of the C and D horizons. It has been pointed out that biologic forces important in soil genesis operate more effectively in the upper profile and, hence, have less influence upon the C and D horizons than they do on B horizons and pans. To take the

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podzolic soils as an example, the B horizons are finer-textured, less permeable, commonly more acid, and higher in organic matter than the C horizons. They generally have more significance to the growth of ordinary crop plants. On occasion, however, the C and D horizons may have extreme properties which are of sufficient importance to plant growth to overshadow those of overlying horizons. For instance, shallow silty outwash in the A and B horizons may be less important to crop production than underlying beds of gravelly outwash. The free drainage and low water-holding capacity of gravel beds can dominate the water regime of the whole soil. This kind of relationship is the exception rather than the rule among soils. By and large, the B horizon or pan is more important than the C or D horizon to plant growth.

In the discussion of various kinds of subsoil layers, including B, C, and D horizons and pans, emphasis has repeatedly been given to the variations in properties. The chemical composition in relation to fertility may be favorable or it may be unfavorable. Reaction may range from alkaline to acid, and the content of organic matter from very low to high. As a general rule, however, most subsoils tend to be low in organic matter and fairly low in most available plant nutrient elements. Physical properties vary as widely as chemical properties. Subsoil textures range from sandy to clays and the water-holding and supplying capacities range from very low to very high. Permeability ranges from rapid to very slow, and the degree of cementation ranges from none to strongly indurated.

Of equal importance to plant growth are the ranges in depth to and thickness of subsoil layers. In some cases, the subsoil lies very near the surface under virgin conditions. For example, the Clarence soils of Illinois on moderately sloping topography have surface soils about 3 to 4 in. thick (Stauffer, 1935). Below this shallow surface layer is a plastic, intractable subsoil. Aandahl (1948) reports wide variations in thickness of the A horizon in Prairie soils formed from the same parent materials but differing in topographic position. By way of contrast, the upper boundary of the subsoil is 2 ft. below the surface in many soils of the Coastal Plain in the region of Red-Yellow Podzolic soils in the United States (Fig. 2). Subsoil layers range in thickness from a matter of inches in a few soils to many feet in others. Whole soils are present in a 6-in. section where bedrock occurs a few inches below the surface. On the other hand, the bedrock under Latosols may be as much as 50 ft. below the present land surface.

The subsoil may consist of relatively uniform materials throughout its depth, or it may comprise several unlike soil horizons. The latter situation is more common among soils generally. For example, there are important differences between the B and C horizons in chernozemic soils. There are also marked differences between the B horizons, fragipans, and the underlying D horizons in many soils of western Kentucky and Tennessee. There is little change with depth below the surface layer in many Latosols. These observations simply reemphasize the variety of subsoils and the wide range in properties whenever any important number of soils is being considered.

## IV. Relationships of Subsoils to Plant Growth

The significance of subsoils to plant growth was emphasized in the introductory paragraphs of this paper without discussion of the relationships themselves. In this section, the effects of subsoil conditions on plant growth will be considered. An attempt will be made to show how some of the major subsoil conditions described in the preceding sections may effect the growth and yields of plants.

As with information on the characteristics of subsoil layers, the data on plant response to those properties are limited. In fact, fewer data bearing on these relationships are available than on the properties themselves. Many illustrations used are therefore drawn from field observations made by the authors, largely in the United States. The wide range of subject matter necessarily covered in the relationships of subsoil conditions to plant growth, together with the scarcity of precise data, preclude comprehensive discussion. It is hoped, however, that a brief discussion and selected illustrations will focus attention on the importance of subsoils to plant growth and stimulate further studies of the interrelationships in the future.

The influence of subsoil properties on plant growth varies with the depth to the subsoil layer or layers as well as with the nature of those layers. The effects of a B horizon when present as part of the undisturbed profile may differ greatly from the effects of a B horizon at the surface. Where deeper subsoil layers have been exposed at the surface by accelerated erosion or other means, their influence on plant growth is commonly accentuated. Furthermore, the problems encountered in the production of crops, pasture, and forest are usually different both in kind and magnitude. Consequently, the discussion of subsoil conditions and plant growth will be divided into two sections, the first dealing with unexposed subsoils where the surface soil is in place and the second with exposed subsoils.

### 1. *Unexposed Subsoils*

Subsoil properties may affect the growth of plants in several ways even though most of the roots are growing in surface soil. A number of the effects of subsoils on plant growth have been discussed by Moon (1938) in outlining relationships of compact subsoils to productivity. First of all, the depth of root penetration is determined in large degree by subsoil properties. Although root distribution is not affected in the same ways for all plants, it is strongly influenced in most cases by the nature of the deeper soil layers. Secondly, the moisture regimes of soils depend as much upon the subsoil as on the surface soil. In fact, moisture regimes may be dominated by the character of subsoil. Thirdly, the subsoil may contribute significant amounts of nutrients and water, if it is readily penetrated by plant roots. In such instances, the nutrients and water taken from the subsoil may contribute substantially toward better growth and higher yields.

*a. Root Penetration.* It is common to speak of deep-rooted and shallow-rooted plants, although the two are not distinct groups. Deep-rooted plants could more appropriately be designated as those which can develop deep root systems under favorable soil and moisture conditions. For example, alfalfa, sweet clover, and apple trees (*Malus* spp.), are generally considered to be deep-rooted plants. Working in Kansas, Grandfield and Metzger (1936) found that alfalfa removed moisture from permeable soils to depths of 25 ft., whereas Myers (1936) noted the roots of two-year-old sweet clover at depths of 13 ft. Sweet (1929) reported apple tree roots well below 10 ft. in certain soils of southern Missouri, and similar observations were made by Browning and Sudds (1942) in West Virginia. Generally speaking, deep penetration occurred in soils which were relatively open and permeable throughout the profile. By way of contrast, the authors have observed alfalfa and sweet clover roots which failed to penetrate claypans and fragipans at depths of 18 to 30 in. Roots extended down to the pans but not into them. Sweet (1929) reports that the roots of apple trees were confined to that part of the soil above the hardpan or claypan. Browning and Sudds (1942) noted that the root systems were shallow in soil types with heavy subsoils. Thus, plants which are ordinarily deep-rooted may be restricted in root penetration by the character of the subsoil.

It is to be expected that plants which are normally shallow-rooted will be less affected by subsoil layers that hinder root penetration. Plants such as corn, oats (*Avena sativa*), cotton (*Gossypium* spp.), tobacco (*Nicotiana* spp.), annual lespedeza, and blue grass (*Poa pratensis*) do not ordinarily have deep root systems. The root systems of these and other common field crops are described by Weaver (1926). A majority of the roots grow in the A and upper B horizons, with some roots extending down into the C and D horizons. This also is true for some trees, as for example, white pine (*Pinus strobus*). Most of the roots are concentrated in the A and B horizons of podzolic soils, and few extend to great depths (Lutz, Ely, and Little, 1937). Although shallow-rooted plants usually have the major part of the root system in the upper soil horizons, this varies with the character of the soil profile. For example, corn roots are almost completely restricted to the A horizon by the claypan in Putnam silt loam in northern Missouri, whereas they extend to depths of 5 or 6 ft. in the friable Marshall and Monona soils of western Iowa. This variation illustrates the flexible rooting habits of some plants. Because of that flexibility, the adaptations of shallow-rooted plants to soils is influenced less by root penetration relationships of subsoil layers than is the adaptation of deep-rooted plants. This is not so true with regard to moisture regimes which will be discussed later.

The B horizons of zonal soils generally permit ready root penetration, although these horizons have considerable ranges in porosity and permeability. On the whole, problems of root penetration are not important unless the B horizons are extreme in texture, drainage, chemical composition, or the like. Difficulties of root growth in B horizons occur where the texture is very coarse or very fine, the reaction is extremely acid or strongly alkaline, and, for many plants, if the layer is very wet or very dry. In B horizons with fair to good supplies of nutrients, enough moisture, and ample pore space, the roots penetrate readily.

The differences in the ability of the roots of plants to penetrate certain kinds of B horizons is worth noting. Taking corn and alfalfa as examples, the root systems commonly extend into and through the B horizons of zonal soils. It is true, however, that alfalfa and other perennial plants are better able than corn to penetrate B horizons that are high in clay, provided the soils are well drained and well aerated. This difference in root penetration is probably related to the length of the growing season and the length of life of the plants rather than to differences in rate of penetration. Corn grows during a relatively short season and its period of root elongation is limited, probably being completed by tasseling time. Alfalfa grows from early spring to late fall, a much longer period. Furthermore, alfalfa root penetration can continue beyond the one season as the plants grow in subsequent years. The differences in root penetration of alfalfa and corn are reflected in adaptation of the two crops to Red-Yellow Podzolic soils with heavy B horizons in the limestone valleys of the southeastern United States (Fig. 2). If properly fertilized, alfalfa makes excellent growth on the soil types with heavy red to brown B horizons which are presumably well aerated. Corn, on the other hand, grows poorly on the same soils, except in years when rainfall distribution is extremely favorable. The restricted root zone of the corn plant apparently fails to make subsoil moisture reserves available for growth.

The penetration of the B horizons of Red-Yellow Podzolic soils by the roots of apple and peach trees is analogous to that of alfalfa. The roots seem to penetrate well-drained B horizons even though they may be fine textured. This is indicated by studies of the distribution of apple tree roots in Newtonia silt loam in southern Missouri (Sweet, 1929) and in Hagerstown soils in West Virginia (Browning and Sudds, 1942). Roots of apple and peach trees extend through the B well into the C horizons, as has been noted by the authors in orchards growing on Red-Yellow Podzolic soils. Fruit trees seem to fare better where the subsoil layers are well drained, permeable, and open to great depths (Sweet, 1933; Oskamp, 1936; Knight, 1942; Wilcox and Knight, 1945). Similar relationships seem to hold for tung trees (Drosdoff, 1950) and for Persian walnuts (Stephenson and Schuster, 1937).

Root penetration is more limited in claypans than in heavy-textured B horizons of moderately well- to well-drained upland soils. Evidence sketched in an earlier section of the paper indicates that claypans have less pore space and are commonly wetter. As a consequence, the oxygen supply is less favorable for many plants, of which corn and alfalfa are examples. Investigations of corn roots by Lawton (1945) and of cherry tree roots by Knight (1942) in compact subsoils indicate that lack of oxygen may limit root growth of those plants. Similarly, Stephenson and Schuster (1937) found that the numbers of roots of Persian walnut trees present were related to the aeration of subsoil layers. Spaeth and Diebold (1938) also emphasize the restriction of root penetration of hardwoods by water tables and poor aeration in soils in New York. Gaiser (1950) uses impermeable subsoil horizons as major criteria in establishing the site index for loblolly pine (*Pinus taeda*) in the Atlantic coastal plain. These studies, coupled with data on the low porosity of claypans, suggest that oxygen may be a limiting factor in the growth of roots of many plants which require ample supplies in the soil for root elongation. This would not hold for plants such as rice, the roots of which normally grow under anaerobic or near-anaerobic conditions.

Equally or more important than aeration in the limited root penetration of claypans is the low pore space and high bulk density. For most cultivated plants, the limited root penetration of claypans can be ascribed, in large part, to mechanical difficulties of root elongation. The authors have observed roots growing in the cracks and channels of claypans without penetrating the structural units in the horizons. Veihmeyer and Hendrickson (1948) found that sunflower roots failed to penetrate compacted samples of clay soils when the volume weights ranged from 1.46 to 1.63. The volume weight of the $B_2$ horizon or claypan of Edina silt loam (Ulrich, 1949) approaches the range given by Veihmeyer and Hendrickson (1948). It seems reasonable that the volume weights of some claypans will reach the values found by Veihmeyer and Hendrickson (1948) and that many will approach these volume weights. Thus, simple mechanical difficulties in root growth can be expected as a general rule in claypans. Coupled with restricted aeration, these mechanical difficulties provide adequate reason for the limited penetration by most plant roots.

Well-developed fragipan and hardpan layers seem to be impervious to nearly all kinds of plant roots. The authors have observed sweet clover and sericea (*Lespedeza cuneata*) roots which penetrated only to the top of the fragipan layer of soils in western Tennessee. At the top of the fragipan the roots turned sideways and extended laterally. This was illustrated most strikingly where part of the surface soil had been removed by accelerated erosion to bring the fragipan within 8 in. of the surface. Most tree roots seem to behave in similar fashion when they reach a fragipan layer. Essentially no roots are present in the pan layer of Leonardtown silt loam (Nikiforoff, Humbert, and Cady, 1948). Sweet (1929) found very few apple tree roots in the fragipan of Lebanon silt loam. Poor growth of apple and peach orchards seems common in soils with distinct fragipans in the southern United States. Examples of difficulties of root penetration can also be found with all types of hardpans. The absence of plant roots in the hardpan of the San Joaquin soils of California is mentioned by Nikiforoff (1941). The difficulties of root penetration in laterite crusts are generally recognized (Pendleton and Sharasuvana, 1946; Kellogg and Davol, 1949; Sherman, 1950). Failure of roots to penetrate a laterite crust occurring at shallow depth in a soil in Hawaii has been observed by one of the authors. Similar lack of root penetration on the part of pine seedlings has also been noted by the authors in the Ortstein or hardpan layers of Ground-Water Podzols in northern Wisconsin.

The difficulties of root penetration in fragipans and hardpans are due to one or more of the following: high bulk density or volume weight, low pore space, restricted aeration, or low fertility status. A volume weight of 1.89 in the pan of Leonardtown silt loam (Nikiforoff, Humbert, and Cady, 1948) approaches the limiting value for sandy soils reported by Veihmeyer and Hendrickson (1948). The bulk density is somewhat lower in the fragipan of Grenada silt loam and in the hardpan of San

Joaquin soils, but the volume weights are still high and the pore space correspondingly low. It seems reasonable that roots will commonly have serious mechanical difficulties in elongation except through cracks in fragipans and hardpans. In most of these pans the difficulties of root growth are accentuated by poor aeration during part of the year. Beyond that, the fertility status of some hardpans, such as laterite crusts, introduces additional difficulties in root growth.

Although so-called shallow-rooted summer crops such as lespedeza, cotton, and tobacco make relatively better growth than crops such as alfalfa and corn when grown on soils possessing fragipan or hardpan horizons, this does not mean that the impervious subsoil horizon is unimportant in their production. Most of these crops will make higher yields if the subsoils are medium-textured B horizons rather than pans. The shallow-rooted crops, however, approach the full potential of their yielding capacity more closely than do deep-rooted crops when grown on soils with pans. This is due in part to the greater resistance of many shallow-rooted crops to short periods of drought. Furthermore, the total yield and, hence, the total water requirement are less for the shallow-rooted crops. One of the most effective methods for the economic utilization of soils with pans is the selection of the better adapted crops.

*b. Moisture Regimes.* The nature of the subsoil exerts an important influence on the moisture relations of the entire soil profile. Subsoil permeability affects percolation rates, which in turn influence infiltration, run-off, and drainage. The amounts of moisture that can be stored in the subsoil are important to plant growth and to run-off. The relationships of subsoil permeability to morphology and crop adaptations have been discussed by Smith and Browning (1946b) and to soil drainage by Wilson, Riecken, and Browning (1946), Kirkham (1947a,b), and Kidder and Lytle (1949). The capacity for storage of moisture has been considered by Veihmeyer and Hendrickson (1938), Cole and Matthews (1939), and Browning (1946).

Subsoil permeability plays an important role in moisture regimes. By restricting percolation after the surface soil has become saturated, it may influence the infiltration rate and the consequent run-off and erosion. An impervious subsoil may cause lateral movement of water and thus result in various types of seepage. It will also tend to make the surface layers wetter in rainy seasons and drier when rainfall is limited. The effectiveness of tile or ditch drains is dependent upon subsoil permeability because it largely governs the rate of moisture movement through the soil. Furthermore, subsoil permeability may determine irrigation practice on many soils.

A horizon of low permeability within the profile will reduce the amount of water that may be absorbed at the surface by reducing the rate of movement through the soil. The layer of minimum permeability may be in the B horizon or in some other part of the subsoil. It may also be a part of the A horizon, as was noted by Van Doren and Klingebiel (1949) in Prairie and related soils in Illinois. Although the importance of slowly permeable layers in the A horizon is recognized, these will not be considered further because they are not part of the subsoil. By and large, the closer the horizon of minimum permeability is to the surface of the soil, the more pronounced and serious are its effects. Once the water-holding capacity of the soil layers above an impermeable horizon has been satisfied, any additional water must move away as run-off with the resulting erosion hazards. Claypans such as those of the Putnam, Edina, and Clarence soils, fragipans such as those of Grenada and Leonardtown soils, or B horizons of extremely fine texture such as those of Colbert soils restrict the percolation of water and result in higher rates of run-off. Consequently, close-growing vegetation is better suited to these and similar soils than are row crops.

The effect of an impervious or very slowly pervious subsoil horizon on the lateral movement and hillside seepage of water has been studied by Kirkham (1947a) in Iowa. Where a subsoil layer was impervious or nearly so, water moved downslope beneath the surface and kept the lower slopes wet. The authors have observed somewhat similar seepage in roadcuts in Edina silt loam where water moved laterally out of the $A_2$ horizon immediately above the claypan. Under some conditions, such lateral movement and seepage may result in soil slips at the contact between the claypan layer and the friable material above. Such slips also occur where loess overlies the impermeable B horizon of a buried soil profile (Aandahl and Simonson, 1950). Similar slips have also been noted by one of the authors in shallow soils formed from sediments high in clay on Okinawa after the passing of a typhoon. Soil slips are of greater importance in soil engineering than in agriculture.

Restricted water movement due to an impervious subsoil layer usually results in reducing conditions and the formation of gleyed layers or horizons. The majority of fragipan and claypan horizons in the humid region show gleying to some degree in their mottled or gray colors. Gleyed horizons may be due to drainage restrictions caused by factors other than impermeable subsoil layers. For example, the absence of adequate drainage outlets in regions with nearly level topography may be reflected in much water-logging and gleying in the soils. Humic Gley and Low Humic Gley soils may be formed under such conditions and have horizons that are strongly gleyed in profiles without appreciable textural differentiation. Within the profile, gleying may be associated with the B, C, or D horizon and even with the A horizon in some instances. In all gleyed horizons, however, moisture relations are unfavorable for a part of the year for plant roots requiring ample supplies of oxygen.

Extremes in moisture conditions are brought about in the surface layers by fragipan and claypan layers. During wet periods, especially in cool seasons when plant transpiration and evaporation from the soil are low, the surface layers may be saturated for long intervals, if they overlie a pan of low permeability. In regions of frost action, the high levels of moisture in the surface layers may result in considerable heaving and winter-killing of crops such as small grains and alfalfa (Post and Dreibelbis, 1942) or in damage to other kinds of plants (Spaeth and Diebold, 1938). During dry and warm periods, the surface soil above the pan loses water rapidly because of plant transpiration and evaporation. Drought conditions for growing plants develop more quickly than they do in profiles with more permeable subsoil layers in which deeper root penetration and greater water movement are possible. The less pervious the subsoil layer and the closer it is to the surface, the more serious are its effects on moisture relations and the more it may reduce yields, as has been shown by Odell (1950). Even if the pan is at considerable depth, it may still have important effects on the moisture regime of the soil, especially in seasons when rainfall distribution is not favorable for plant growth. Thus, soils with distinct fragipans, claypans, or comparable layers as part of the profile are not well suited for winter crops subject to heaving or summer crops that are not drought resistant.

Land drainage is more difficult and expensive, as a rule, if soils have claypans or fragipans as parts of their profiles. Tile drainage is of little benefit if tile lines are placed below the level of the pan or impermeable horizon, as is indicated by the studies of Kirkham (1947b) and of Kidder and Lytle (1949). Because the more prominent and less permeable fragipan and claypan horizons are usually within 2 ft. of the surface, tile drains must be closely spaced and at fairly shallow depths. In such cases, effective drainage is limited to soil within a few feet of the drain, according to the studies of water table height between tile lines made by Kirkham (1947b). The importance of subsoil permeability to drainage is also evident from the observations of Wilson, Riecken, and Browning (1946) on effectiveness of level terraces on some soils and the drainage possibilities in others of southern Iowa. In many soils with pans, it can thus be expected that crops such as alfalfa and corn will not grow much better after the installation of tile drains than they did before. Drainage ditches are subject to most of the limitations of tile drains in soils with slowly permeable subsoil layers. Generally speaking, ditches must be closely spaced and relatively shallow if they are to be effective. Consequently, the practice of "bedding" or plowing the land so as to leave a number of empty furrows fairly close together to serve as shallow ditches is often followed on level or nearly level soils with tight subsoils. In some instances, the moisture conditions in the soils cannot be improved appreciably. The best use of soils with distinct claypans or fragipans and a topography that precludes effective use of drainage ditches is the production of shallow-rooted plants that can withstand wide ranges in moisture conditions.

Impervious subsoil layers are serious handicaps to the use of soils for irrigation. For the most part, irrigated soils in semi-arid and arid regions need periodic leachings to remove soluble salts. In some soils, the removal of soluble salts is a necessary first step in reclamation (Powers, 1946). More and more emphasis in evaluating areas for irrigation has therefore been given during recent years to the possibility of drainage and salt removal (U.S. Regional Salinity Laboratory, 1947). In a preliminary report on the soils of a township in Spink County, South Dakota, Westin (1950) stresses subsoil permeability in appraising potential suitability for irrigation. Special mention is made of solonization and its effects in the development of claypans in certain soils that are poorly suited to irrigation. Unless the deeper layers will permit percolation of water, soils are in serious danger of becoming saline and unfit for further use soon after irrigation is started. The problems due to salt accumulation are some of the most troublesome in irrigation agriculture in the United States, as indicated by the establishment of a regional laboratory for their study. The effects of the subsoil on moisture regimes in soils being irrigated are clearly of great importance to the problems of salt accumulation and removal, aside from the usual significance to infiltration rates and storage capacities.

Emphasis has been given to impervious or slowly permeable subsoils in discussing moisture regimes. Perhaps their effects are more prominent generally in this and in other countries. Mention should, however, be made of subsoils which have very low water-holding capacities. For example, the subsoils of Lakeland sand and Rubicon sand can hold very little water. Most of the water which penetrates into the subsoil moves rapidly downward to the water table. Similarly, the gravelly subsoils in soil types formed from outwash terraces, kames, and eskers in the north-central United States have extremely low water-holding capacities. The droughty character of the soils is usually reflected in a characteristic vegetation. For example, sand pine (*Pinus clausa*) commonly grows on St. Lucie sand in Florida and jack pine (*Pinus banksiana*) on Rubicon sand in northern Michigan. Both species of pine can survive where moisture supplies are so low as to restrict the usefulness of the soils for crop or forest production. Sandy or gravelly subsoils tend to make soils excessively drained wherever topographic position and elevation will permit water to move away readily into natural drainage channels.

*c. Nutrient and Water Supplies.* It has been pointed out that fertility levels, on the whole, are lower in subsoils than in surface soils. This is more generally true in terms of readily available nutrients than in terms of total quantities. The total amounts of nutrients in subsoils represent vast and potentially significant reservoirs for crop production, if they could be used effectively (Bradfield, 1946). Furthermore, there are many subsoils relatively high in one or more nutrient elements. Examples of soils with high levels of available phosphorus and potassium are given in earlier sections of this paper on nature and properties of subsoils. Many additional examples could be cited if space permitted. Thus, the present and future importance of subsoil fertility should not be overlooked in programs for crop and forest production. This is especially true with the forest production, in which the use of fertilizers is seldom feasible.

Subsoil fertility becomes significant to the growing plant after the roots have extended into the subsoil layers. The effects of subsoil fertility seem to be reflected in observations of early responses of corn, cotton and other crops to phosphate fertilizer, responses which disappeared as the season advanced. For example, Stanford and Nelson (1949) noted response to phosphate fertilizer in growth of corn during the early part of the growing season but failed to find significant differences in crop yields. The lack of yield response in a number of such cases can be attributed to the tapping of supplies of phosphate in the subsoil.

It should be recognized that a high level of fertility in the subsoil is no substitute for an adequate fertility level in the surface soil. The seed must be planted and the seedling become established in the surface soil. If the fertility level of this layer is too low, that may retard early growth enough to lower yields significantly even though adequate amounts of the same nutrients are present in deeper layers of the soil. If the weather and other conditions affecting growth are unusually favorable, a low fertility level in the surface soil may not be critical. With unfavorable growing conditions, however, any restriction on early growth may have serious effects on subsequent yields. Hence, the level of fertility in the surface soil cannot be neglected even though subsoils are high in one or more nutrient elements.

As in the case of subsoil fertility, the moisture in the deeper layers becomes available chiefly after the roots reach those layers. Because the influence of subsoil properties on root penetration has been discussed in a preceding section, the capacity of the subsoil to supply water to roots already present will be considered in this section. The capacity of the subsoil to supply water to growing plants depends on its capacity to hold water and upon its permeability. For the most part B, C, and D horizons have satisfactory water-supplying capacities unless they are of extreme textures. Claypan layers generally have high water-holding capacities but can provide relatively little moisture for most crops. Mention has already been made of the limited root penetration of claypans, and the movement of water through them is slight and slow. Furthermore, the high clay contents permit such pans to hold large quantities of water unavailable to plants. Fragipan and hardpan layers are usually low in their capacities to hold water or to supply it to growing plants.

Many subsoil layers make significant contributions of water to growing plants. These include the B horizons of most zonal soils and the C or D horizons of a smaller number. For example, alfalfa withdrew moisture from all parts of the soil profile and even from sediments beneath it in Kansas (Grandfield and Metzger, 1936). It removed all water available to plants between depths of 3 and 8 ft. in Marshall silt loam over a period of three years in Iowa (Browning, 1946). The withdrawal of moisture from deeper subsoils by alfalfa is complete enough in some instances to make certain Prairie soils unsuitable for new alfalfa seedings and orchards for a number of years. Cole and Matthews (1939) point to the role of subsoil moisture in the production of wheat in the Great Plains, where there is an annual cycle of depletion and replenishment. Burrage (1948) found that the soil moisture remained at fairly high levels at a depth of 18 in. in soils of open areas, whereas it dropped as the growing season advanced under a 35-year-old stand of pine.

The contribution of water to growing plants will depend upon the nature of the plant itself and upon the character of the subsoil. Alfalfa growing on well-drained soils with medium to heavy-textured B horizons seems to be able to make good growth during periods of limited rainfall when corn on the same soils shows evidence of damage. This illustrates the possible effects of differences in root systems of plants. Another example of subsoil moisture relationships may be observed when corn is grown in the same locality on permeable Alluvial soils and on soils with distinct pans in their profiles. On the Alluvial soils, corn can stand relatively long periods without rain before yields are reduced. The corn growing on the soils with pan horizons, however, will suffer from lack of moisture and produce lower yields, even though similar fertility levels are maintained in both groups of soils.

In a discussion of the use of subsoil moisture by plants, attention should also be given to shifts in water requirements of plants with the advance of the growing season. In studies conducted in southwestern Iowa, Browning (1946) found that corn and oats used more water in the early and middle portions of the growing season than in the latter part. Alfalfa, on the other hand, used much water continuously throughout the growing season. Possible contributions of moisture for plant growth by subsoil layers thus may depend upon the nature of the subsoil, the character of the plant, and the distribution of rainfall.

Subsoils have importance to plant nutrition because many do provide substantial amounts of nutrients and water. The extent to which plants can draw nutrient elements and water from the subsoil is not well known, but considerable significance to plant nutrition can be recognized. At the same time, available data clearly show that very large reservoirs of plant nutrients exist in subsoils. As has been suggested by Bradfield (1946), these supplies of plant nutrients deserve much more attention. They are much larger than commercial deposits of mineral fertilizers. Moreover, they are already distributed widely in the places where they would ultimately be used for plant growth. It seems, therefore, that much more recognition should be given to the potential importance of subsoil reserves.

### 2. *Exposed Subsoils*

Subsoil layers have been exposed over a relatively large aggregate area of land through accelerated erosion. Some exposures of subsoils are due to excavation or to grading but these are only of local importance. Exposed subsoils are mainly B or C horizons, but they may be various types of pans or D horizons. These exposed subsoils do have considerable significance to the production of crops, pasture, and forest. In this section, the extent of exposed subsoils and some of the problems in their utilization for plant production will be outlined. Major attention will be given to conditions in the United States, but it is expected that the discussions will apply to some degree in other parts of the world. Readers interested in an appraisal of the world situation are referred to a report on soil conservation by Baldwin *et al.* (1948).

Estimates of the amount of surface soil removed in various parts of the United States are quoted by Utz and Kellogg (1938). Of particular interest are the 225 million acres, 12 per cent of the land area of the United States, considered to have suffered "serious erosion," i.e., to have lost 75 per cent or more of the surface soil. Over an important part of this acreage, subsoil layers are exposed at the surface or mixed with the remainder of the A horizon in tillage operations. For most of this area, subsoils are now more important to plant growth than they were formerly. In addition to the seriously eroded areas, there are approximately 775 million acres, according to Utz and Kellogg (1938), which have suffered significant erosion. The soils affected by accelerated erosion are widely distributed over the country and do pose problems in management for crops, pastures, and forests. As already mentioned, subsoil materials are also exposed in cities and towns where grading is necessary or where excavated materials are spread over building lots. These exposed subsoils are of importance to a great number of people in the growing of lawns and gardens, but they have a limited total area.

The reliability of erosion estimates has been discussed by Bradfield (1949) who has called attention to the limitations on accuracy in such estimates. The difficulty of making reliable estimates is also suggested by the studies of Aandahl (1948), showing the wide ranges in thickness of the A horizon of Prairie soils under virgin conditions. Furthermore, there are complications in appraising the significance of subsoil exposures to production, even after reliable estimates of affected areas have been prepared. In an analysis of yields of corn, wheat, oats, and potatoes in the United States and Europe over a period of four decades, Weitz (1926) found that acre-yields showed a slight upward trend. This was true both for the long-cultivated soils of Europe and for the more recently opened lands of the United States. Smith (1950) has recently discussed the effects on certain great soil groups of their use for crop production since the United States was first settled. He contends that some soils have been improved and others have deteriorated under production practices of the past. No attempt will therefore be made to appraise the accuracy of estimates or the actual significance of subsoil exposure in the United States. It is enough for the purpose of this paper to call attention to the large aggregate areas of exposed subsoils. These areas present problems in the growing of plants frequently different from those associated with the same soil prior to erosion.

The occurrence of exposed subsoils may take several forms. For example, exposed subsoils commonly occur as spots or patches on the Gray-Brown Podzolic and Red-Yellow Podzolic soils of the United States (Fig. 2). As a general rule subsoils are exposed in a part of an area which has undergone severe erosion. It should also be recognized that subsoil layers may be exposed over the entire area of former fields where accelerated erosion has been very severe or where A horizons were very thin. Thus, the geographic nature of subsoil exposures varies as much as does the character of the subsoil itself.

In humid regions water erosion is more important than wind erosion. Subsoil exposures are therefore more common on sloping lands, particularly where frequent cultivation has been practiced. On the whole, sloping soils are likely to have subsoil horizons that are more favorable for plant growth than do soils on level sites. The soils on moderate slopes seldom have B horizons with extreme physical and chemical properties. By way of contrast, the various kinds of pans are more common in level soils. Thus the subsoils most frequently exposed in humid regions are less likely to be unfavorable for plant growth than those of soils not susceptible to erosion. Exceptions to this generalization do occur, as for example, in the Shelby and associated soils which have fine-textured subsoils.

In drier regions the texture of the surface soil is more important than slope in determining susceptibility to wind erosion. Consequently, slope itself becomes a less important factor in determining subsoil exposure. As in humid regions, however, pan layers are more common in level soils than in sloping ones. Because wind erosion may be as effective on level areas as sloping sites, the probabilities of exposure of pans is greater. On the whole, the problems of using exposed subsoils in dry regions seem to be as great as or greater than those in humid regions.

Exposed subsoils are being cultivated in a number of places and they constitute part of the plow layer in others. They will continue to be cultivated for a variety of reasons wherever the available technology can provide methods that will yield fair incomes. In many places subsoil exposure has a spotted occurrence in fields. Prominent knolls or comparable sites with subsoil at or near the surface are frequently scattered through the fields as small individual areas. In such fields it would be impossible to discontinue cultivation of the subsoil exposures without abandoning the entire field. Another factor which encourages continued cultivation of subsoils is the lack of capital for purchase of new land and the difficulties of moving from one farm to another. In many places, farmers thus face and will continue to face a number of practical problems in the cultivation of exposed subsoils.

In addition to the significance of exposed subsoils to cultivation they also have an important bearing on forest management in humid regions. Many badly eroded areas in the southeastern United States are abandoned and left idle to support whatever vegetation will grow, although some are planted to trees. Many of these eroded areas are used for forest if they are used at all. As pointed out by Hoover (1949), these exposed subsoils present serious problems in forest management.

The problems of growing plants will differ from one kind of subsoil to another. In some cases physical problems will be more important, and in others the improvement and maintenance of fertility will be critical. Consequently, the problems in improving and maintaining favorable physical properties and fertility levels will be considered separately in the following paragraphs.

*a. Physical Problems.* There are a number of problems of improving physical properties in the use of subsoils. This is true whether the subsoils are to be used for cultivated crops, for pasture, or for forest. In cultivation there are problems of tillage, of seed bed preparation, of crust formation and control, of seedling emergence in relation to crust formation, of infiltration, and of movement of water within the soil. In pastures there are problems of establishing stands and the types of tillage necessary to seed the grasses and legumes. In reforestation there are difficulties of starting seedlings and of getting them established afterward. Some of these difficulties can be remedied in part by soil treatment. For example, the addition of manure and crop residues to increase organic matter content, fertilization to encourage more vigorous growth, and careful choice of crops may improve subsoils for cultivation. In most instances the improvement of physical properties is beneficial to plant growth, and in some instances it is essential to satisfactory production.

The kind and severity of physical problems varies with the type of subsoil. As the type of subsoil changes, so do the problems of improving it for cultivation or for pasture. If the subsoil is of medium texture, granular structure, and friable consistence, the problems in cultivation are minor. On the other hand, a subsoil with high clay content, such as a claypan, is extremely hard to manage with present methods. The physical problems can be predicted largely from the subsoil properties outlined in some detail earlier. At this point, only a few examples will be given to illustrate the effects of physical properties of subsoils on plant growth. The B horizons of Gray-Brown Podzolic soils, Prairie soils, and Latosols, the claypans, the laterite crusts, and C and D horizons have been selected as illustrations. These subsoils represent a wide range of physical problems in their utilization. Types of B horizons or pans not discussed here will fall between two or more of the examples.

*(1) B horizons of Gray-Brown Podzolic soils.* The nature of Gray-Brown Podzolic B horizons has been discussed in Section III, 1a. These B horizons are commonly enriched in clay with 2:1 lattice type minerals dominant and are a little lower in organic matter than the A horizon. This discussion will largely be concerned with those B horizons clearly higher in clay than the A horizons. Unless clay contents are higher, the problems of tillage, water relations, and the like are much the same as they are for the A horizons.

When markedly higher in clay, the B horizon is far more plastic and sticky than the A horizon and has a greater tendency to crust upon drying. The optimum moisture range for cultivation is also narrowed sharply. In general the higher the clay content, the more difficult are the problems of cultivation. If the clay is dominantly of the 2 : 1 lattice type, as for example in Weller silt loam, a soil formed from loess in southern Iowa and northern Missouri, exposure of the B horizon by erosion forces abandonment. Known methods do not include practical procedures for improving the physical properties to the point where the subsoils are suitable for crop production. On the other hand, if the B horizon is lower in clay and more friable, as in Fayette silt loam, it can be cultivated successfully and will yield satisfactory crops under good management. By and large the cost of production is increased, but the total effect is relatively small. Rost (1939) found that yields on B and C horizons of Fayette silt loam could be as high as those from the A horizon. Demortier *et al.* (1950) report consistently higher yields of wheat, oats, and sugar beets from the B horizons than from the A horizons of soils in Belgium which seem to be members of the Gray-Brown Podzolic group formed from coarse loess. On the whole, it seems that physical properties of the B horizons are more important to their possible usefulness for plant growth than are their chemical properties.

*(2) B horizons of Prairie soils.* These B horizons were described and discussed in an earlier section of the paper concerned with chernozemic soils. They are related to the B horizons of Gray-Brown Podzolic soils in that the clay fraction is also high in 2 : 1 lattice type minerals. B horizons of Prairie soils are slightly to markedly higher in clay and much lower in organic matter than the A horizons. As with Gray-Brown Podzolic soils, however, the physical problems of tillage and moisture relations are essentially similar for the A and B horizons, unless there are major differences in clay contents.

As a general rule, Prairie B horizons are more plastic and sticky than the A horizons even when clay contents are similar. The much greater amounts of organic matter in the A horizon make it mellow and friable by comparison. When the differences between the A and B horizons in clay content are small, however, they seem to be of little importance to plant growth. Aandahl (1949) reports no relationship between yield of corn and thickness of A horizon in well-managed Marshall silt loam. On the other hand, there were differences of as much as 30 bushels per acre between a soil with 4 and one with 12 in. of A horizon, if management levels were low. After a few years of proper fertilization Bauer *et al.* (1945) obtained yields from a desurfaced plot of Tama silt loam in northern Illinois about equal to those from a plot with the A horizon present. The Tama and Marshall soils are similar but not identical in the clay contents of the A and B horizons. Among Prairie soils the B horizons are not generally fine textured. There are soils such as Seymour silt loam, however, in which the B horizon is high in clay. Such B horizons, like that of Weller silt loam, cannot be improved sufficiently by practical methods now known so as to be suitable for crop production.

*(3) B horizons of Latosols.* The character of Latosol B horizons, as described in an earlier section of the paper, differs in many respects from those of Gray-Brown Podzolic and Prairie soils. Latosol B horizons are much higher in free oxides and in 1:1 lattice type minerals. The physical properties are consequently rather similar to those of A horizons. It is true that the B horizons are commonly lower in organic matter than A horizons, but this has little effect on friability of the subsoil. The friability of subsoils is emphasized in most discussions of Latosols (Roberts, 1933; Sherman, 1949; Kellogg, 1950). In fact, the name "red loams," proposed for a group of Latosols refers directly to subsoil friability.

On the whole the B horizons of Latosols are as friable and permeable as are the A horizons. Bennett and Allison (1928), in their discussion of soils of Cuba, state that the subsoil is as easy to cultivate as the surface soil. Van der Merwe (1926), in a study of productivity of the subsoil of a Latosol or a closely related type, concluded that fertility rather than physical character was the limiting factor in plant growth. Proper fertilization made the subsoil as productive as the surface soil. Problems of crop production on Latosols have been less extensively studied than they have on the Gray-Brown Podzolic, Prairie, and other soils of temperate zones. Nevertheless, it does seem true that physical characteristics are seldom as important as fertility in limiting plant growth. In passing, it might be added that the B horizons of Red-Yellow Podzolic soils fall between those of Latosols and Gray-Brown Podzolic soils in their physical characteristics with respect to plant growth. Their physical properties can be improved more easily than can those of Gray-Brown Podzolic soils. At the same time, the physical properties are somewhat less favorable than those of Latosols.

*(4) Claypans.* These have been emphasized in earlier parts of this paper because of the many problems common to the growing of plants on claypans or on soils with claypans. Problems are common when the claypan is a part of the soil profile or when it has been exposed at the surface. The problems of improving physical properties of claypans are serious whether they are the B horizons of Planosols, the B horizons of Solonetz soils, or nongenetic claypans.

Claypan horizons and layers are especially dense and intractable. They are very plastic and sticky when wet, firm when moist, and very hard when dry. Infiltration rates are extremely low, and the movement of moisture within the claypan is negligible (Ulrich, 1949). The claypans are extremely high in clay, usually of the 2:1 lattice type, with all the difficulties this implies. They furnish an extreme expression of difficult problems in improving and maintaining favorable physical conditions for plant growth. By and large, exposed claypan subsoils are barren of vegetation. Where plants have been able to establish themselves, they are extremely poor even though special efforts have been made to provide satisfactory soil conditions.

Various means have been used in attempts to improve physical properties of exposed claypan subsoils. Heavy additions of organic matter will alleviate conditions somewhat, but it is hard to work manure or other organic matter into the soil. It is also difficult at best and impossible at worst to grow plants on the claypan and so to add organic matter in the form of roots and tops. Consequently, with our present state of knowledge, there are no known methods of improving the physical properties adequately for plant growth without outlays of money which exceed the value of the land after reclamation. The possibilities for growing plants, whether they be crops, pasture, or forest, are permanently lowered by exposure of claypans under existing knowledge in soil science and present economic conditions.

*(5) Laterite crusts.* As pointed out in an earlier section, these are probably the most widespread and extensive among the various types of hardpans. They are exposed in important areas in Africa, Asia, and South America.

Laterite crusts support very poor plant growth when exposed and left intact. Similarly, the concretionary laterite layers also support thin stands of poor vegetation. The crusts described by Sherman (1950) in Hawaii have been observed by one of the authors and when exposed, were essentially barren of vegetation. The illustrations of Pendleton and Sharasuvana (1946) indicate very poor plant cover. A scraggly growth, including a high proportion of ferns (*Gleichenia* spp.) covers the concretionary bauxite in the Palau Islands (Bridge and Goldich, 1948). Observations made generally indicate that plant cover on laterite crusts or concretionary laterite is extremely poor.

There seems to be little possibility of improving physical properties of laterite crusts. Breaking up the crusts is an expensive process. Without tremendous expense in the operation, the crusts would still remain in lumps or pieces so coarse as to be unfavorable for plant roots. Furthermore, the crusts, even if well pulverized, would certainly remain chemically unfavorable for plant growth and might still be poor physically. Consequently the laterite crusts seem to be largely beyond utilization with our present state of knowledge.

*(6) C and D horizons.* In some areas, the A or B horizon or both have been removed by erosion. In other areas, well-developed A and B horizons were never present although most soils seem to have had at least very thin A horizons. So far as can now be determined, however, there are a number of soils which consist mainly of C horizons or, in cases where geological unconformities exist, of C and D horizons.

The influence of these horizons upon plant growth can be predicted largely from the properties of the layers themselves. Where the C horizon is of medium texture and is deep over unconforming sediments, it may be as good as or better than many uneroded soils. Soils of this sort are common along the Mississippi River bluffs where the loess deposits are deep. Where these areas are not too steep for cultivation, the soils produce satisfactory crops of many kinds. Fertilization or the addition of organic matter to provide nitrogen is commonly necessary. Similar soils occur in the deep loess along the Missouri River and in parts of the Great Plains. Alway, McDole and Rost (1917) found that plant growth on soil samples taken at 1-ft. intervals down to 8 ft. in soils from loess in Nebraska was dependent upon added fertilizer. The physical properties were generally satisfactory, but the fertility status was not favorable for a number of crops. Plants such as alfalfa, which are strong feeders on phosphorus, were able to grow satisfactorily on samples from deeper portions of the profile. Similar observations have been made by Rost (1939) and Bauer *et al.* (1945).

If the C horizon is either very fine or very coarse in texture, the relationships to plant growth are strikingly different. For example, the acid parent materials of Susquehanna soils are of little value for plant growth. These acid clays have the physical properties of claypans. At the other extreme are the gravels and sands of the Guin series, also found in the southeastern United States, which have little value for plant growth. These materials, where they are exposed at the surface, support very poor vegetation of any kind. It should be recognized that soils developed from such sediments are poor, even when the profile is intact.

These examples of the effects of physical properties of C horizons on plant growth illustrate only a few of the many possibilities. The great bulk of soils will fall between the extremes which are favorable for plant growth or which may be essentially useless. There are, consequently, all degrees of problems in the use of exposed C horizons for crop production, pasture, or forest.

The effects of erosion are especially serious when a coarse-textured or fine-textured D horizon is exposed by removal of A and B horizons with fair to good physical properties. This can follow erosion of soils such as the Lexington, Brandon, and Tippah series in western Tennessee and Mississippi. All these soils are formed from shallow loess over acid sediments. Underneath the loess in Lexington soils are very sandy sediments. In the Brandon soils the D horizon consists of gravels, whereas in the Tippah soils it comprises acid heavy clays. Once the sandy D horizon of Lexington soils is exposed by erosion, the areas become essentially useless for crop production because of the poor water relations and increased erosion hazard. The gravel beds under Brandon soils are even poorer, whereas the heavy clay D horizon of the Tippah soils have little usefulness for plants of any kind.

In this discussion, no mention has been made of D horizons consisting of consolidated rock. The effects of exposure of such D horizons by erosion are obvious and need little discussion. The areas of this kind throughout the world are essentially waste land.

*b. Fertility Problems.* It is quite generally believed that subsoils are much less fertile than surface soils. This inference is based largely on observations of poorer plant growth on many freshly exposed subsoils. It also seems to be based in part upon the generally lower amounts of organic matter in the subsoil. The inference is valid in some instances and unwarranted in others. If fertility is defined as the amounts of and balance among plant nutrient elements, most subsoils (the B, C, or D horizon or pan) are lower in nitrogen than the surface soils. They are also commonly lower in organic phosphorus and in forms of phosphorus readily available to plants. On the other hand, the subsoils are more often than not higher in calcium, magnesium, and potassium available to plants. The total quantities of plant nutrients other than nitrogen are substantially higher in the subsoils in many instances and lower in others. Relatively few studies have been made to evaluate the fertility status of subsoils, but it is possible to call attention to certain relationships.

Experiments have been conducted with Gray-Brown Podzolic, Prairie, Latosol, and other soil groups to ascertain the productivity of subsoils. Mention has already been made of the studies by Alway, McDole and Rost (1917) in Nebraska. Rost (1939) studied effects of fertilization with phosphorus and nitrogen on B and C horizons from Prairie, Gray-Brown Podzolic, and Brown Podzolic soils. His findings indicate that levels of nitrogen and phosphorus must be raised before yields from the deeper horizons can be comparable to those from the upper horizons. Bauer *et al.* (1945) in Illinois, has found that the yields of crops from the deeper subsoils were equal to those of the A horizon after a period of several years with proper fertilization. Van der Merwe (1926) considered fertility relations the limiting factor in a study of Latosols in South Africa. He does add that the yields from surface soils are also low unless fertilizer is applied, which is to be expected of soils of that group under most circumstances. Additional evidence of this kind from experiments in Ohio is mentioned by Bradfield (1949). Attention should be called to the fact that the subsoils studied seem to have fair to good physical properties. Under such circumstances, the plant nutrient status or fertility levels are limiting factors in plant growth. If, on the other hand, the physical conditions of the subsoils were unfavorable for plant growth, as is true with claypans and laterite crusts, the additions of plant nutrients would have little meaning. It is not possible to generalize widely about the fertility of subsoils.

It should be recognized that subsoils may contain larger quantities of some nutrient elements in available form than does the surface soil. For example, C horizons of Prairie soils formed from loess in Iowa are higher in dilute-acid soluble phosphorus than the A or B horizons (Pearson, Spry, and Pierre, 1940). This phosphorus does not seem to be available to corn, but can be utilized by sweet clover or alfalfa. The amounts of exchangeable calcium or potassium are appreciably higher in the B and C horizons of Tama silt loam than they are in the A horizon (Smith, Allaway, and Riecken, 1950). They may also be higher in some Red and Yellow Podzolic soils (Dyal and Drosdoff, 1943). Available potassium is appreciably higher in the deeper horizons of Sequoia soils derived from shale in the valleys of eastern Tennessee than it is in the surface layers. Experience with these soils indicates that alfalfa can obtain enough potassium from the deeper layers to grow successfully, once it has passed the seedling stage.

The measurement and evaluation of fertility levels of subsoils are not essentially different from problems encountered with surface soils. There do seem to be differences in levels of available plant nutrients between the surface soils and the subsoils in many cases. There are also differences within profiles in capacities to fix elements such as phosphorus. Nevertheless, attempts can be made to measure the levels of available elements, especially calcium, magnesium, nitrogen, phosphorus, and potassium. Where deficiencies of other elements are suspected, the levels present in the subsoil should also be investigated. On the whole, the kinds of problems encountered in measuring and interpreting fertility levels of subsoils fall within the range of those encountered in surface soils. It seems that these problems can be attacked by means of the same general procedures.

## V. Management of Unexposed Subsoils

Although the effective use of exposed subsoils for the production of plants is important, it seems that proper management of the subsoil as a part of the soil profile is even more significant. Over the years little attention has been given to the possible effects of the deeper layers of the soil on plant growth. Major interest has been directed at the furrow slice; it has even been said that farmers make their living from the uppermost 6- or 8-in. layer. The fallacy of this statement is obvious from studies of root distribution of apple trees (Sweet, 1933) and of the uptake of moisture by corn (Browning, 1946). At the same time, it is readily apparent that we know little about the actual significance of subsoils to plant growth except in extreme cases. We also know little about ways and means of handling subsoils in place. Furthermore, there are few answers available to questions about the effects of present management practices on subsoil. Are the subsoils improving or deteriorating? At the present time, an adequate answer to this question does not seem possible, although current practices include methods which can reasonably be expected to have harmful effects upon subsoil properties. Discussion of some of our current practices may focus attention on the need for more knowledge about subsoil behavior.

### 1. *Subsoil Compaction*

Heavier machinery is now being generally used on farms, especially in the United States. Larger tillage and harvesting implements are being used, and there have been sharp increases in the number of tractors on farms, even during the past five-year period. With the increased numbers of tractors and with limited labor supplies on many farms, soils are often cultivated before they reach optimum moisture contents for tillage. Thus, the soils may be compacted or even puddled. This compaction occurs particularly in the surface layer, but some effects extend into the deeper profile as well. In the Corn Belt of the United States, for example, compression of subsoils must obviously follow when harvest goes forward in fields so wet and soft that tractor and wagon wheels sink 8 to 10 in. into the soil. There seem to be plow soles or compact layers immediately beneath the furrow slice in a number of soils in the sugar cane area of Louisiana where heavy machinery is in general use. Maximum compaction doubtless occurs in the deeper A horizon, but the effects will likely extend into the B and even the C horizon in some instances. Hoffer (1947) has called attention to problems of subsoil compaction in the Corn Belt.

Huberty (1944) found that pore space was reduced as much as 50 per cent in the uppermost layers and had also been reduced in the subsoils in irrigated areas in southern California. The compaction was enough to interfere with penetration of the soil by rain and irrigation waters.

Edwards and Ableiter (1942) mention a compact layer or plow sole immediately beneath the furrow slice in sandy Chestnut soils of western North Dakota. This plow sole, which forms as a laminated layer in the upper B horizon, is hard enough to be strongly resistant to penetration by a spade. When dry, the plow sole can hardly be cut by a spade unless the blade is held at an angle of about 45 degrees to the surface of the plow sole. Once crushed or broken, however, the layer is friable.

Some evidence is available to show that compaction of soil follows the use of tractors even at optimum moisture contents. Weaver (1950) notes that annual tractor tillage of Davidson soil in bins at Auburn, Alabama, introduces evident compaction to depths of 9 in. when moisture contents were near the optimum for plowing. Free, Lamb, and Carleton (1947) call attention to soil compaction due to tractor operation on podzolic soils in New York, whereas Parker and Jenny (1945) noted compaction in certain soils in California and attributed it to traffic and cultivation. Kachinsky (1927) also noted some compaction through loss of pore space in preliminary trials with two types of tractors. In all these studies most of the compaction occurred in the surface soil but the effects seem to extend downward into the subsoil to some degree.

Subsoil compaction seems to occur in some soils simply as a result of long-continued cultivation. Bradfield (1936) noted that the apparent specific gravity had increased and the pore space had decreased in Paulding clay after many years of cultivation. Moreover, the yield of corn was 20 bushels per acre in a field that had been cultivated for many years, whereas, it was 80 bushels across the fence where the first crop was being grown. He also mentions the fact that tile drains must now be placed at one-half the spacing that was adequate when the soil was first cultivated. Changes in physical properties occurred from the surface to a depth of at least 3 ft. Similar observations have been made elsewhere. Hoover (1949) compared the percolation rates in virgin and cultivated areas of Vance soils, members of the Red-Yellow Podzolic group with a heavy-textured yellowish red subsoil. At a depth of 24 in. the percolation rate in the cultivated area was 0.02, and in the virgin area 1.5 in. of water per hour, and total porosity was 40 and 48 per cent, respectively. Laws and Evans (1949) reported that the porosity at a depth of 30 in. in Houston Black clay was lower in a cultivated field than in a near-by virgin area. Houston Black clay is closely related to the dark subtropical clays of the broad chernozemic group shown in

Fig. 1. Hoover (1949), as well as Laws and Evans (1949), found that yields on the long-cultivated areas were lower than on comparable virgin areas. Part of the yield reduction seems attributable to unfavorable subsoil conditions.

The possible effects of soil compaction on root growth are indicated by studies of Veihmeyer and Hendrickson (1948) who found that sunflower roots did not penetrate sands with volume weights near 1.75 or clays with volume weights somewhere between 1.46 and 1.63. Their studies also suggest that some compaction of soil material occurred at low moisture contents and that plow soles may be formed by ordinary tillage. Such plow soles could interfere with water movement and thus hinder root penetration, particularly in wet periods.

Soil types with medium to medium-light-textured subsoils of a friable nature produce high yields for a long period of time under continuous cultivation. Many of the Alluvial soils of medium texture in the flood plains of the Mississippi, Illinois, and Missouri rivers have produced high corn yields year after year for a long period of time. These illustrations suggest that subsoils of a favorable nature, from a physical point of view, are less likely to give difficulty under intensive cultivation than are subsoils with less favorable physical properties. Data are too limited, however, to conclude that even the subsoils with favorable physical properties may not deteriorate under long and intensive cultivation. The limited data available suggest that current soil management practices are resulting in the development of unfavorable subsoil conditions in many situations.

### 2. *Prevention and Correction of Subsoil Compaction*

It is important for efficient sustained production and for soil conservation that efforts be made to prevent or overcome unfavorable subsoil conditions wherever possible. Some of the possible approaches to subsoil amelioration include deep tillage and subsoiling, the growing of deep-rooted plants, and a wider use of pasture and sod crops to reduce frequency of row crop production on cultivated lands. An attempt will be made to illustrate possible applications of these approaches from experimental data and from field observations.

*a. Deep Tillage.* The influence of deep tillage on crop yields has been a controversial subject for many years. In a few instances crop yields seem to be better, but generally results are negative. The apparent discrepancies in the effects of deep tillage may be due to subsoil differences that were not recognized and described. Work done in England indicates that the depth of tillage had little influence on crop yields (Russell and Keen, 1938). The soils under study were probably members of the podzolic or related groups. Similarly, Hume (1943) found little or no beneficial effect from deep tillage on the yields of corn, wheat, and clover from chernozemic soils in South Dakota. Crop yields were not improved by deep tillage of a soil underlain by a heavy claypan in Illinois (Smith, 1925). On the other hand, Woodruff and Smith (1946) report slight increases in the yield of corn after disturbance and liming of the claypan of a soil in Missouri. Deep tillage and subsoiling to depths of 12 to 15 in., sometimes to 18 in., are practiced rather commonly on some of the Red-Yellow Podzolic soils with medium-heavy B horizons. Farmers believe that erosion is reduced and yields increased when deep tillage precedes each row crop, but quantitative data on the effects of the practice are not available. Unpublished data of the Tennessee Agricultural Experiment Station indicate little effect of tillage depth on yields of corn from Dewey and Decatur soils. Field observations do indicate beneficial effects from moderately deep tillage, however, on certain soils underlaid at shallow depths by D horizons of soft shale. Subsoiling breaks up the shale easily and thus seems to increase the effective rooting zone of crops. By and large, the published data and the observations of the authors suggest that deep tillage has a limited usefulness in the general improvement of subsoils but may be helpful in some instances.

When soils with fragipan layers occur on moderate slopes and are cultivated frequently, they commonly suffer erosion which brings the fragipan layer close to the surface. Under such conditions, moderately deep tillage to break up part of the fragipan layer seems to result in better growth of many crops, though not of alfalfa. The beneficial effect of the deep tillage seems to be expansion of the rooting zone, analogous to that in certain shallow soils overlying shale. Deep tillage of soils with fragipans has been most beneficial when the entire pan layer could be broken up by the operation. Unfortunately, fragipan layers are often several feet thick and pose serious difficulties to effective subsoiling. Furthermore, the power requirements and costs increase sharply as depth of tillage increases.

Deep tillage or subsoiling does seem to have promise of considerable usefulness under some circumstances, as for example in soils that have thin fragipans not far below the surface. Furthermore, it seems that hardpans, fragipans, and laterite crusts remain broken and permeable after one effective tillage operation. In many other subsoils, where deep tillage has some promise, however, it must be repeated, usually at frequent intervals. Because the costs are high and multiply rapidly as greater depths are reached, the expense and probable returns must be weighed carefully against those for alternative approaches. Possible alternative management practices for cultivated lands include: (1) Attempts to promote deeper rooting by the selection of crops and liberal fertilization to encourage vigorous root growth, (2) The adoption of a rotation which would involve less frequent growth of row crops, and (3) The selection of crops better adapted to the unfavorable subsoil conditions.

*b. Deep Rooting of Plants.* It is suggested frequently by agricultural workers that the development of deep root systems will improve subsoil conditions and promote higher yields. This suggestion generally refers more to the improvement of physical properties than to fertility levels, as for example, the suggestion by Hoffer (1947) that legumes with tap roots be grown to combat tendencies toward plow sole formation.

Few data can be found which give quantitative measures of the effects of deep roots on physical or chemical properties of subsoils. It does seem reasonable, however, that the deep roots might improve some subsoils. Major attention will therefore be given to subsoil layers which are not particularly favorable for root growth and which do have some possibility of improvement. These are mainly B and C horizons of medium to heavy texture, very low fertility levels, or both, and claypans.

Deep rooting can seldom be expected in soils with well-developed fragipan or hardpan layers as parts of their profiles. Field observations indicate that roots seldom penetrate such layers. Consequently, it does not seem probable that subsoils consisting of fragipan or hardpan layers can be improved by the growing of deep-rooted plants. It may be possible in exceptional instances. Chevalier (1949) reports that a laterite crust disappeared in forty years under a good stand of forest. Comparable experiences with fragipans and most hardpan layers, however, seems to be lacking.

The improvement of physical properties of subsoils has been inferred from increased percolation of water in some instances. Page and Willard (1946) noted that water removal from Paulding clay in Ohio was related to the cropping history of experimental plots. After heavy rains, the water stood in puddles on continuous corn plots when corn-oats-sweet clover rotation plots were dry enough to cultivate. Wilson and Browning (1945) report higher yields and better percolation on plots previously in deep-rooted legumes, when compared to plots used for row crops, all on Marshall silt loam which is ordinarily considered to have a good subsoil. Olmstead (1946) also noted better percolation in certain soils in Kansas after the growing of sweet clover. The studies were designed primarily to determine the effects of different crop rotations on soil aggregation. The soils studied in Iowa and Kansas are representatives of the chernozemic groups, whereas, Paulding clay is a Humic-

Gley soil. Mention has been made earlier of the higher percolation rates in the subsoil of Vance sandy loam under virgin conditions as compared with cultivated conditions (Hoover, 1949). All these observations indicate that subsoil layers can be improved for moisture penetration and plant growth by the growing of deep-rooted species. At the same time, it should be recognized that it is difficult to sort out the causative factors for improved growth or percolation when physical properties of the surface soil are also affected by the treatments.

Stauffer (1948, 1950) has called attention to compact subsurface conditions developing in many soils in Illinois. Hoffer (1947) has also emphasized the importance to crop growth of plow soles developing in a number of soils in the Midwest. Many of the soils in Illinois in which a compact subsurface layer has developed are members of the Humic-Gley or Weisenboden group, which includes Paulding clay studied by Bradfield (1936) and by Page and Willard (1946). These soils seldom have distinct B horizons, and it is therefore difficult to give proper identification to the horizon in which the compaction occurs. Moreover, the boundaries between horizons are diffuse and gradational. Thus, the compacted layer might be identified as the lower A, the B, or the upper C horizon in the various soils in which it has been found. The texture of the compacted layer is commonly silty clay loam to silty clay. Stauffer (1950) suggests that more frequent growing of grasses and deep-rooted legumes along with other improved soil management practices will help to correct the compact subsurface conditions. Sweet clover and red clover (*Trifolium pratense*) grow satisfactorily on the Humic-Gley soils in most seasons, but alfalfa is less well adapted. It will grow well on the associated Prairie soils, some of which also show subsurface compaction.

It is possible that sod crops with medium-deep to medium-shallow root systems would be equally effective in many soils in controlling subsurface permeability, particularly if liberal use is made of lime and fertilizer to encourage vigorous root growth. Red clover, alsike clover (*Trifolium hybridum*), and even white clover (*Trifolium repens*) might maintain subsurface permeability under good management programs. Van Doren and Klingebiel (1949) report considerably higher subsurface permeability on fertilized plots than on unfertilized plots of Cisne and Elliott soils. Cisne silt loam, a Planosol with a claypan at about 18 in., had a permeability rate at the 7- to 10-in. depth of 0.69 on a fertilized plot as compared to 0.31 in. of water per hour on an unfertilized plot. On Elliott silt loam, a Prairie soil developed from medium plastic glacial till, the permeability rates at the 8- to 11-in. depth were 2.61 and 0.70 in. per hour for fertilized and unfertilized plots, respectively. Parker and

Jenny (1945) found that subsurface compaction at the 6- to 12-in. depth in an irrigated orchard in California was corrected by the growing of a cover crop and discontinuing tillage temporarily.

Alfalfa is probably the outstanding example of a deep-rooted crop which might improve subsoil conditions. With adequate fertilization and good seed bed preparation, alfalfa roots seem able to penetrate fairly heavy clay horizons that are adequately aerated. The use of B horizon colors as guides to aeration in the podzolic and latosolic soils was mentioned in a preceding section on nature and properties of subsoil layers. In many heavy subsoils it seems that lack of aeration is a primary obstacle to the penetration of alfalfa roots. There is less likelihood of this kind of trouble in the regions of chernozemic and desertic soils. Alfalfa roots are generally thought to develop channels and enlarge pores in the subsoil, with resultant improvement of aeration. As the alfalfa roots die and decay after having penetrated the subsoil, they may leave channels that persist for a long period of time. As far as is known to the authors, no data are available on the length of time such pores will persist. Quantitative information on the life of channels left by deep roots would be highly desirable.

Another point which would bear investigation is the need for penetration of roots to a more permeable layer in order to exert beneficial effects on subsoil properties. In podzolic soils from medium-textured materials, alfalfa roots would ordinarily penetrate through the B into the more permeable C horizons. This would also be true in some of the latosolic soils, but not in all of them. Many Red-Yellow Podzolic soils have C horizons that are very similar in texture to the B horizons (Simonson, 1949). Furthermore, a large number of soils are underlain by fine-textured residuum or sediments extending to great depths. The Decatur and Dewey soils of eastern Tennessee are examples of soils underlaid by deep residuum, through which even alfalfa roots cannot be expected to penetrate.

Field observations indicate that alfalfa roots seldom penetrate claypan layers. As discussed earlier, this seems to be caused by poor aeration in the claypan and to mechanical difficulties of root elongation. Sweet clover may penetrate claypan layers a short distance. It has a shorter life and reaches full development much more quickly than alfalfa. Apparently, sweet clover roots are also less sensitive to poor aeration. Judgments as to factors responsible for differences in root penetration by the two legumes must be speculative. More complete information about factors which restrict penetration of roots into claypans will be necessary before it will be possible to suggest how alfalfa, sweet clover, or other plants may be used more effectively in the improvement of the dense, intractable horizons.

Among the deep-rooted legumes, sericea (*Lespedeza cuneata*) should be more useful in the future than it has been in the past. It is well adapted to much of the Red-Yellow Podzolic region in the United States (Fig. 2), where the climate is unfavorable for red clover and many soils are not well suited to alfalfa. Unless fertility levels are medium to high, however, sericea growth is very slow. Furthermore, like other plants, its roots commonly fail to penetrate fragipan layers. Despite its higher fertility requirements, sericea seems to be a legume that might find a greater place in soil management programs in warm-temperate humid regions.

Legumes are generally given first consideration among deep-rooted plants which might improve subsoil conditions. Grasses may also be helpful, however, in maintaining or improving the physical properties of subsoils. In an earlier section studies of root distribution of native grasses in chernozemic soils of Nebraska were cited (Weaver and Darland, 1949). In the Prairie and Chernozem soils grass roots commonly penetrated to depths of 4 and 5 ft. or well through the B and into the C horizons. Even in Planosols with distinct but not prominent claypans, the roots of several of the grasses extended through the B horizon into the C horizon. Difficulties of root penetration were evident in the B horizon. Roots were most numerous in the A horizons without exception, but large numbers were present in many of the C horizons, especially the more friable ones. It is generally known that permeability is much higher in a bluegrass sod than in the same soil from a long-cultivated field. Even where the field had been well managed, the percolation rate is much lower than in grass sods. For example, Van Doren and Klingebiel (1949) report permeabilities 15 to 30 times as great in sod as in cultivated areas of the same soil. The formation of channels of significant size cannot be ascribed to the fine fibrous grass roots but some organic matter is left in the deeper profile when the roots die and decay. It has also been observed generally that grass roots promote soil aggregation, examples of which may be drawn from the studies of Wilson and Browning (1945) and Olmstead (1946). What the exact influence of grass roots on subsoils may be is not known, but it does seem reasonable that the effects observed on A horizons may extend into the B horizons to some degree.

The gradual deterioration of structure in soils such as Paulding clay under cultivation suggests that trees were able to improve physical properties of soils, especially in the deeper horizons (Bradfield, 1936). Lutz and Griswold (1939) state that tree roots may influence soil morphology by pushing soil material aside as they grow, by leaving channels when they decay, and by the mixing of soil materials when trees are blown over by the wind. Their studies of Podzols and Brown Podzolic soils in profile pits in New Hampshire indicated significant disturbance and mixing of horizons by windthrow of individual trees in ordinary forest stands. Page and Willard (1946) suggest that the gradual decay and disappearance of coarse tree roots originally present in soils under forest may be reflected in gradual deterioration of physical properties of soils under cultivation. Yeager (1935) found that trees growing in Chernozem and Humic-Gley soils of eastern North Dakota had about 97 per cent of their roots, on the average, in the uppermost 4 ft. Inasmuch as trees are not the indigenous vegetation on Chernozems, growing conditions are less favorable for them than they are on podzolic soils in more humid regions. Even so, some tree roots penetrated to depths of 10 ft. and many to depths of 4 ft. More direct information on the influences of tree roots on soil properties may be taken from experience with shifting cultivation in the Belgian Congo (Kellogg and Davol, 1949). Rotation systems are followed in which crops are planted in corridors or strips that alternate with the native forest. Optimum rotations provide for cultivation of a corridor from four to eight years, after which it is kept in forest about as long. This practice is essential to the maintenance of satisfactory physical properties of the soils. Chevalier (1949) also emphasizes the importance of ''bush fallow'' in maintaining soils in good physical condition in French Guinea. Problems of structure maintenance in the cultivation of Latosols seem to differ greatly from those common to podzolic soils. For the most part, granulation is encouraged and sought for in podzolic soils, whereas it must be controlled and sometimes prevented in Latosols. These various observations indicate that tree roots may serve in several ways in the improvement of subsoil conditions or in the maintenance of satisfactory conditions for plant growth. As with data on the effects of other types of roots, however, precise information as to the kinds and magnitude of effects are still lacking.

Important effects of deep roots seem to be the ''opening up'' of tight subsoils, the improvement of aggregation in some cases, and the shifting of soil materials in others. These are mainly physical effects. Deep roots may also have influence on fertility. It is clear that they add organic matter upon death and decay. Furthermore, some plants are able to utilize nutrient elements in forms not available generally. For example, legumes are able to draw on the large supplies of dilute acid soluble phosphorus in the C horizons of the Ida and related soils of western Iowa. Corn is unable to use the forms of phosphorus present and may show serious deficiencies while growing beside sweet clover which shows none. On the other hand, a crop of corn can be grown successfully on the same soil after the stand of sweet clover has been plowed under and had an opportunity to decay. Thus, deep roots may in some cases also affect fertility status of subsoils by shifting the form in which plant nutrients are present.

### 3. *Liming and Fertilizing Subsoils*

It has been pointed out in an earlier section of the paper that many subsoils are low in available plant nutrients and that some are extremely low. Furthermore, some of them, especially the B horizons of podzolic and latosolic soils are generally moderately to strongly acid. Investigations cited earlier in the paper, such as those of Van der Merwe (1926), and Rost (1939), suggest that it might be possible in some soils at least to raise the levels of subsoil fertility and thus improve growth.

Deep placement of fertilizer and lime was strongly advocated a few years ago but receives much less emphasis now (Jones and Rogers, 1949). A number of experiments in placement of fertilizer beneath the furrow slice were conducted in Indiana by Scarseth *et al.* (1943) who report improved yields. Drake and Stewart (1950) also found that growth was better when fertilizer was placed at a depth of 8 in. than when it was placed at a depth of 3 in. These depths, as well as those used in the Indiana experiments, are still within the A horizon of most soils. Consequently, the experiments do not bear directly upon the possibility of improving B, C, or D horizons by liming and fertilization. Moreover, the results of experiments with deep fertilizer placement have not been conclusive as indicated by Jones and Rogers (1949), who note that the practice is now being given much less attention.

Tiedjens (1948) advocates the liming of subsoils coupled with deep tillage and heavy fertilization for soils of southeastern Virginia that appear to be members of the Low Humic-Gley group. Preliminary experiments indicate low fertility levels, especially a lack of available calcium, restricted root development in a number of the soils. As a consequence of liming to overcome acidity to depths of 1 ft. or more in combination with subsoiling to depths of 20 in., yields of crops have been improved markedly, as has root growth and soil drainage. Woodruff and Smith (1946) also recommend liming and subsoiling of claypans in soils of northern Missouri, of which Putnam silt loam is the chief example. Modest increases of yield were reported as a consequence of liming and subsoil shattering in experiments which had been in progress for a short time. Pohlmann (1946) found that numbers of nodules and fibrous roots were greater after liming of soil layers between depths of

8 to 16 in. and 16 to 24 in. In the soil studied, which was a member of the podzolic group, the deeper layer at least lay within the B horizon. Along with the data on liming of subsoils, mention should be made of the observation that calcium alone does not insure good structure. Bradfield (1936) reports an almost impermeable layer that was calcareous in the deeper profile of St. Clair silty clay loam in Ohio. He also calls attention to the deterioration of soil structure in Paulding clay which is high in exchangeable calcium and may be slightly calcareous. Thus, the presence of calcium in large quantity does not of itself insure favorable conditions for growth. Similar statements would apply to other nutrient elements. Nevertheless, it does seem that deficiencies of one or more nutrient elements in available form may restrict root development in a number of subsoils. This is suggested by the work of Alway, McDole, and Rost (1917), Rost (1939), Van der Merwe (1926), and Tiedjens (1948). These data indicate possibilities of better plant growth after liming and fertilization where levels of available nutrients are low in the B and upper C horizons. More exact data are needed, however, as a basis for adequate evaluation of these possibilities on different soils, particularly in view of the mechanical difficulties of placing lime or fertilizer much below plow depth.

### 4. *Utilizing Subsoil Nutrients*

The desirability of making better use of the large amounts of nutrients in subsoils seems obvious, not only for improving plant growth but also to conserve our relatively limited stocks of commercial fertilizer materials. For example, Bradfield (1946) estimates that there is more potassium in the uppermost 4 ft. of soil in the state of New York than in all the known commercial potassium reserves in the United States. Could methods be developed to tap even a minor part of this and similar reserves in subsoils, much smaller quantities of commercial fertilizers would serve to maintain high yields. As Bradfield (1946) explains, this philosophy is at variance with the "bank account" point of view in soil management. This point of view assumes that the removals of nutrients by crops, leaching, or erosion must be offset pound for pound through fertilizer additions. Comparisons of total amounts of plant nutrients in subsoils versus those in fertilizer deposits and in surface soils clearly show that the reserves in subsoils are tremendous. Far more attention could well be given to utilization of these reserves, even though it does require the development of new approaches and methods in soil management.

Perhaps a first approach to the greater utilization of subsoil nutrients is the growing of more plants which extend their roots deep into the soil.

The possible effects of deep-rooted plants has been considered in a previous section on the prevention and correction of compact subsoil conditions. In subsoils with a large part of the plant nutrients in available forms root penetration to the horizon in question is the only thing needed to make absorption of the nutrients possible. In some cases, the nutrient elements are present in forms available to some plants and not others. An example was given in the preceding section of the ability of sweet clover to use forms of phosphorus not available to corn in the C horizons of certain soils in Iowa (Pearson, Spry, and Pierre, 1940). The choice of plants therefore promises to be important in many instances, if subsoil nutrients are to be utilized. More study might well be given to the differential abilities of plants to use various forms of nutrient elements. Furthermore, deep-rooted plants might absorb nutrients from the subsoil and, upon death and decay, leave a part of these subsoil nutrients in or on the surface soil.

If the proportions of nutrients in available form are small in the deeper soil horizons, procedures to make them more available must be employed before deep-rooted plants can use them effectively. Soil drainage to improve aeration, the introduction of organic matter, the encouragement of microbiological activity, and the improvement of permeability might all contribute to increased availability of plant nutrients in subsoil. Beyond that there is also the question raised by Bradfield (1946), "Do we want to prevent erosion or do we want to control erosion? Is there an optimum degree of erosion which we should first determine and then strive for in developing soil management systems?" It may even be desirable in some soils to encourage removal of part of a weathered and leached A horizon so that plant roots may more easily extend into the B and C horizons.

The possible gains implicit in the utilization of nutrient reserves in the B, C, and D horizons are tremendous. The quantities of plant nutrients in subsoils, as compared with those in surface soils and in mineral fertilizer deposits, resemble the amounts of energy obtainable through fission of a pound of uranium as compared to oxidation of a pound of hard coal. These tremendous potentialities were visualized by Bradfield (1946) when he wrote: "To learn how to unlock the practically unlimited reserves of practically all plant nutrients, except nitrogen, which lie beneath the soil is a task that will require men skilled in many different sciences. In many cases the soil will have to be drained to a greater depth. Aeration will have to be improved. Conditions will have to be made more favorable for flora and fauna which can gradually penetrate the soil to greater depths. All the factors mentioned above will need to be brought to interact to produce a better structure in the soil. The physical chemist will have to work closely with both the soil mineralogist and the soil microbiologist if he is to develop a real understanding of all the phenomena that are involved."

Imagination and ingenuity of the first rank on the part of scientists in a number of disciplines will be necessary in any successful effort to unlock these practically unlimited reserves of plant nutrients in subsoils. Yet, if the ultimate objective of full utilization of subsoil nutrients is but partly achieved, the prospective benefits to the production of crops, pasture, and forest will be enormous.

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# The Management of Alfalfa Meadows After Seeding

C. J. WILLARD
*The Ohio State University, Columbus, Ohio*

CONTENTS

*Page*
I. Introduction . . . . . . . . . . . . . . . . . . . . . . . . 94
II. The Effect of Cutting Systems on Amount and Quality of Hay . . . 94
  1. Yield of Hay at Successive Stages of Maturity . . . . . . . 94
  2. Protein in the Hay . . . . . . . . . . . . . . . . . . . 95
  3. Protein per Acre . . . . . . . . . . . . . . . . . . . 95
  4. Leaves in the Hay . . . . . . . . . . . . . . . . . . . 95
  5. Fiber in the Hay . . . . . . . . . . . . . . . . . . . 96
  6. Minerals in the Hay . . . . . . . . . . . . . . . . . . 96
  7. Carotene Content of the Hay . . . . . . . . . . . . . . . 96
  8. Number of Days between Cuttings . . . . . . . . . . . . 96
III. The Effect of Different Systems of Cutting on Root Reserves, Sustained Yield, and Longevity of Stands . . . . . . . . . . . . . 97
  1. The March of Food Reserves in Alfalfa Roots during a Year of Cutting at Favorable Times . . . . . . . . . . . . . 97
  2. The Time of Making the Last Cutting in the Fall . . . . . . 98
  3. The Effect of Weather and Climate on the Storage of Food Reserves in Roots of Alfalfa . . . . . . . . . . . . . . . 100
  4. The Effect of Repeated Cuttings at Specified Stages on Root Reserves and Hay Yields in Current and Following Years . . . . 101
  5. How Many Cuttings a Year? . . . . . . . . . . . . . . . 101
IV. The Relation of Various Factors to the Time of Cutting . . . . . . 102
  1. Indicators of Stage of Maturity . . . . . . . . . . . . . 102
  2. Shoots at the Crown . . . . . . . . . . . . . . . . . . 103
  3. Leafhoppers . . . . . . . . . . . . . . . . . . . . . . 104
  4. Can Fertilizers Prevent the Bad Results of Early and Frequent Cutting? . . . . . . . . . . . . . . . . . . . . . . 104
  5. Varieties . . . . . . . . . . . . . . . . . . . . . . . 105
  6. Which Cutting Is of Highest Quality? . . . . . . . . . . . 105
  7. Market Grade of Hay . . . . . . . . . . . . . . . . . . 105
  8. Modifying the Time of the First Cutting by Spring Clipping . . . 105
  9. Bacterial Wilt . . . . . . . . . . . . . . . . . . . . . 106
  10. Height of Cutting . . . . . . . . . . . . . . . . . . . 106
  11. Percentage of Dry Matter in the Green Plants . . . . . . . 106
  12. Alfalfa-Grass Mixtures . . . . . . . . . . . . . . . . . 107
V. Summary of Practical Recommendations for Cutting . . . . . . . 107
VI. Cultivation of Established Alfalfa : . . . . . . . . . . . . . 108
VII. Other Weed Control Methods in Alfalfa . . . . . . . . . . . . 109
References . . . . . . . . . . . . . . . . . . . . . . . . 110

## I. Introduction

After a good stand of alfalfa is established, its production and longevity depend on management practices, of which the following are most important: (1) cutting, (2) cultivation, (3) weed control, (4) insect control, (5) fertilization, and (6) irrigation.

Disease control might be included, but it is very seldom undertaken as a separate operation with alfalfa. This paper will discuss the first three topics, especially those connected with cutting the crop.

Much of the most significant work on these problems is not recent; it is the intent of this paper to summarize and correlate this older work with new work available in order to give a comprehensive picture of the interacting factors involved in the cutting of alfalfa.

## II. The Effect of Cutting Systems on Amount and Quality of Hay

Alfalfa is usually cut two to several times a year, so that both the number of cuttings a year and the development of each crop are important in determining the yield. The development of each crop will be considered first (Salmon *et al.*, 1925; Kiesselbach and Anderson, 1926; Sotola, 1927, 1933; Spuy and Stead, 1931; Woodman *et al.*, 1933, 1934; Willard *et al.*, 1934; Agronomy Department, Ohio Agricultural Experiment Station, 1938; Dawson *et al.*, 1940; Armstrong *et al.*, 1942; Brown and Munsell, 1942).

### *1. Yield of Hay at Successive Stages of Maturity*

The growth curve of a crop of alfalfa, like that of other plants, is sigmoid, beginning slowly, followed by a long fairly uniform period of rapid growth, and then slowing down to a much lower rate. During the rapid growth period in alfalfa, increases in yield of 75 to 100 lb. per acre per day are general. Shortly after bloom starts, the rate of growth slows down and most experiments indicate a larger yield of hay at full bloom than at any other stage. The decrease in yield after full bloom is due to the death and dropping of lower leaves and small branches and to attacks of the omnipresent forage-feeding insects. Alfalfa is not determinate in growth, and if soil and weather conditions are favorable, the full bloom stage may last for two to three weeks, as the main stem lengthens and new flower shoots are produced. There is usually a slow increase in total yield under these conditions, at the expense of hay quality.

### 2. *Protein in the Hay*

Alfalfa hay is valued for its protein content. All studies in all regions where alfalfa is grown show that this decreases steadily with maturity. The difference in crude protein content from bud stage to full bloom, usually a period of about two weeks, is usually from 2 to 3 per cent, sometimes more. The rate of decrease is more rapid in humid regions than under irrigation.

This decrease in protein is due to several factors. Diseases attack the leaves, causing them to drop; insects eat more of the high protein parts of the plant than the fibrous stems; in dense stands the lower leaves die from shading. Since the percentage of protein in alfalfa leaves is usually about double that in stems, this loss of leaves reduces the protein in the hay. The correlation of leaf percentage and protein content is of the order of $r = 0.67$ to $r = 0.77$ (Kiesselbach and Anderson, 1930; Willard *et al.*, 1934).

The percentage of protein is also reduced by dilution arising from the accumulation of carbohydrates, especially fiber, without a proportionate increase in total protein.

The crude protein at bud stage will range from 20 to 26 per cent; at full bloom from 14 to 18 per cent. The crude protein in the leaves will vary from 18 to 27 per cent and in the stems from 8 to 16 per cent, the high figures being from very immature stems.

### 3. *Protein per Acre*

For the man who feeds his hay, the best time to cut is usually the time he harvests the most protein per acre. Since per cent of protein goes down and yield goes up as alfalfa matures, the most protein per acre will be reached at a stage before the greatest yield per acre and usually when about one-tenth to one-half the plants are in bloom.

### 4. *Leaves in the Hay*

The percentage of leaves in the hay decreases regularly as the alfalfa becomes more mature. Pre-bud hay may contain 50 to 60 per cent of leaves, or even more in some harvests late in the season; seed-stage hay may contain perhaps less than 30 per cent of leaves. The exact figures in any given field will vary with insect infestation, infection with leaf spots and other diseases, the vigor of growth (tall, heavy growth will contain a lower percentage of leaves), the density of the stand (more of the lower leaves are shaded off in dense stands), and the variety, but there will be a steady decrease in percentage of leaves as the crop matures. The only occasional exceptions to this are found when new growth comes up in old growth. At times there may be enough of this new growth to overbalance the loss of leaves on the preceding growth, and to increase the percentage of both leaves and protein in the total hay as harvested.

### 5. *Fiber in the Hay*

The fiber in the hay increases with age much as the protein decreases. The percentage in the hay will range from about 23 to 37 per cent. The fiber in the leaves is about 15 to 18 per cent; that in the stems from 38 to 43 per cent (Sotola, 1933). Since the variations in the percentages of fiber in the leaves and in the stems separately are small compared with the variations in fiber in the total hay, it seems that much of the variation in fiber of hay cut at different stages is due to differences in the percentage of leaves at the successive stages.

Woodman *et al.* (1933) called attention to the extensive lignification of fiber which takes place in alfalfa even by the bud stage. The fiber in very young alfalfa was highly digestible, 75 to 86 per cent, but at the bud to bloom stages the digestibility of the fiber was 43 to 46 per cent.

### 6. *Minerals in the Hay*

The percentage of ash usually decreases as the crop becomes more mature, though exceptions are recorded. The percentage of calcium changes very little, sometimes increasing. Phosphorus usually decreases slightly, at least by full bloom. The percentage of phosphorus in leaves is considerably higher than that in the stems. The leaves contain 2 to 3 times as much calcium and magnesium as the stems, but the stems contain more potassium than the leaves.

### 7. *Carotene Content of the Hay*

In general the percentage of carotene diminishes as the alfalfa becomes more mature, being positively correlated with the percentage of protein, and negatively correlated with the yield of dry matter per acre (Hauge, 1934; Snyder and Moore, 1940; Thompson, 1949; McGuire and Jackobs, 1951). Douglass *et al.* (1933) found more carotene in early bloom-stage hay than bud-stage hay.

### 8. *Number of Days between Cuttings*

The number of days a crop of alfalfa requires for its development will vary with climate, season, and the stage of maturity chosen, but usually ranges from 30 to 45 days. In most of the United States, it is rare for less than at least 38 to 40 days between cuttings to give highest yields, either for the cutting or the season. Lack of moisture will cause alfalfa to bloom in a shorter time than is required normally, at times less than 20 days, but with very low yields. Alfalfa will develop faster on rich soils than on poor soils, and in midsummer than in fall or spring.

The first cutting grows more slowly and cannot be included in calculations of the number of days for development except by arbitrary and unrealistic assumptions. At Columbus, Ohio, for example, alfalfa is always obviously, often vigorously, growing by April 1, but the half bloom stage of maturity is reached about June 7, or 67 days later. The last cutting before freeze-up also grows slowly, and often does not bloom at all.

## III. The Effect of Different Systems of Cutting on Root Reserves, Sustained Yield, and Longevity of Stands

The previous discussion has concerned the development of only one crop of alfalfa. When we try to cut at a predetermined stage through the year, or several years, we at once find that the time of cutting one crop may affect the development of the next, because cutting the tops stops the storage of food materials in the roots. Consequently the growth of roots must be studied in determining the best stage of cutting alfalfa.

Several early root studies suggested this for alfalfa, but it remained for Graber (1924), Nelson (1925), and Graber *et al.* (1927) to demonstrate by root harvests, root analyses, and repeated experiments that root growth and top growth of alfalfa were interdependent and to point out a majority of the practical applications to alfalfa management. Others have since added to and filled in parts of the picture.

### 1. *The March of Food Reserves in Alfalfa Roots during a Year of Cutting at Favorable Times*

Graber *et al.* (1927), Willard (1930), Willard *et al.* (1934), and Grandfield (1935) have shown the normal course of reserves in a stand of alfalfa well stored with food reserves in February. As growth starts, there follows a very rapid reduction in stored reserves in the roots—the most extensive of the year. The loss may amount to 500-600 lb. per acre or more and includes both carbohydrate and protein reserves. The percentage of nitrogen and of all carbohydrates in the roots decreases sharply.

Normally this depletion continues until nearly the time the first flower branches appear, but the minimum point is highly dependent on the weather. (See Section III 3.) Grandfield (1935) finds the lowest point about May 1 in Kansas: it is about May 15 in Ohio, and still later in Wisconsin. After the minimum point is reached, there is a gain in reserves, slow at first, until the alfalfa is cut. When the tops are diseased or yellowed by leafhoppers, storage is small or none.

After cutting, reserves of both protein and carbohydrates are again drawn on to produce new growth. Willard (1930) reports the average loss in weight of roots per acre two weeks after cutting as 177 lb., but this is subject to a high standard error and may not be the minimum point. Grandfield (1935) and Brown and Munsell (1942) indicate that the minimum point is later than this. The percentage of nitrogen in the roots drops by 0.2 to 0.3 per cent, or sometimes more, during recovery from cutting.

This cycle of storage and exhaustion of root reserves continues with each cutting until the final hay crop is cut, and the fall growth, normally not removed, has started. If this fall growth starts 7 to 10 weeks before final freeze-up so that a considerable photosynthetic area is produced, there will be a very large gain in root reserves, usually the largest of the year. Alfalfa withstands severe frosts, so killing frost dates are not significant *per se* for alfalfa. This gain in the fall results from reduced vegetative growth and reduced respiration because of lower temperatures, while photosynthesis remains active. This relation of respiration to temperature is universal, but has been accurately measured for alfalfa by Thomas and Hill (1937a). They found respiration to increase fourfold from 0° to 20°C.

Gains of root reserves amounting to as much as 1,200 lb. per acre and averaging 600 lb. per acre (air-dry weight) have been reported during this period. The percentage of total carbohydrates in the roots increases regularly. The relation between starch and sugars varies. The proportion of sugars increases during hardening for winter (Mark, 1936; Grandfield, 1943) and remains higher than the amount of starch throughout the winter. The percentage of nitrogen in the roots also goes up steadily during fall growth. The percentage of nitrogen in the roots usually increases still more from fall to spring, presumably because of reduction in the amount of stored carbohydrates by respiration.

### 2. *The Time of Making the Last Cutting in the Fall*

The discovery that the fall cutting was critical in humid regions led first to the practical rule: "There ought always be left a growth of alfalfa at least 12 inches high to serve as a protection to the crowns" (Wing, 1916). This is a satisfactory rule, but many disliked to "waste" so much good hay. If it were only as a mulch, there would seem to be cheaper mulches. Many experiments have been conducted (Graber *et al.*, 1927; Grandfield, 1934, 1935, 1943; Mark, 1936; Silkett *et al.*, 1937; Graber and Sprague, 1938; Rather and Harrison, 1938; Brown and Munsell, 1942; Torssell, 1943; Nelson, 1944; Willard, 1950; Jackobs, 1950) to determine the effects of cutting at different dates in the fall, the dates ranging from those dictated by Wing's rule, which requires making the last cutting about four weeks before the average date of killing frost, and so about eight weeks before final freeze-up of alfalfa, to taking off the growth as nearly as possible at final freeze-up, so that little or no new growth was produced.

The results indicated increasing injury, as evidenced by greater winter injury, poorer stands, and lower yields per acre, as the last cutting was made later, until a period approximately three to four weeks before final cessation of growth, or about the time of the average date of killing frost. The damage from cutting as late as possible was always less than from cutting two to four weeks earlier, but practically always there was highly significant injury, even at this period.

The late cuttings resulted in alfalfa going into the winter with lower reserves, since the tops which might have produced them were cut, and the reserves present were drawn on to produce new growth. Because of the late new growth, the late-cut alfalfa also went into the winter in an unhardened or less hardened condition. These effects of root reserves were shown to be more important than the mulch considered in the older rule.

Theoretically, cutting just before the ground and tops freeze, but after fall accumulation of root reserves, should not result in injury. Some tests (Rather and Harrison, 1938) approximated this, but it seems that, practically, some new growth will follow almost any cutting, with consequent damage. Furthermore the value of the tops purely as a mulch is important at times (Arny, 1926), as was demonstrated by the partially successful substitution of straw for the alfalfa tops (Garver, 1946; Willard, 1950).

It may be possible to make the last cutting too early (Grandfield, 1935). This is entirely reasonable, as good root storage depends on healthy tops to produce photosynthate. Alfalfa developing after an early August cutting may become diseased and yellow before October 1, so that it can hardly be efficient in photosynthesis, and yet the presence of that growth inhibits the starting of new growth until late in the fall when increased new growth uses reserves at a damaging time (Willard *et al.*, 1934, pp. 103-104).

Some have replaced the last cutting with pasturing. This has the same effect as cutting (Rather and Dorrance, 1938). Alfalfa is grazed at the top, and once the growing shoot is nipped off, recovery is likely to be from the crown, with resulting exhaustion of root reserves.

These experiments and many others show that for any humid area there is an optimum time of making the last cutting in the fall. Any satisfactory cutting system for a humid region must determine this period first of all. Because of the much greater storage of reserves throughout the season in irrigated areas, these effects are very slight there (Jackobs, 1950) and need not be considered in practice.

### 3. *The Effect of Weather and Climate on the Storage of Food Reserves in Roots of Alfalfa*

Botanists have long known that plants grown under dry conditions will have a higher proportion of roots to tops than those grown under wet conditions.

As alfalfa culture moved into humid regions from irrigated regions and grassland climates, it was evident that it could not be cut as carelessly as it had been under irrigation (Wing, 1916, p. 296). Willard *et al.* (1934) showed conclusively that rainfall during the season affected root reserves. Alfalfa at the end of the first cutting year, cut three times, contained from 2,000 to 2,500 lb. per acre of roots following a wet growing season; at the end of a very dry growing season, with poor hay yields, the roots amounted to 3,500 to 4,500 lb. per acre. Even four-cutting plots had high reserves in this year, and the stands in the four-cutting plots continued good the next year. Experiments since have confirmed these results repeatedly and significantly (Willard, 1950).

The fact that dry weather or climate favors root storage is the most important principle, practically, in the management of alfalfa in humid regions. It explains many conflicting results of time-of-cutting experiments in different years. It also explains the much better results with early cutting of alfalfa in irrigated regions and in Oklahoma-Kansas-Nebraska-South Dakota than farther east.

The physiological reason for the increased storage in dry seasons and climates is not clear. It cannot be due to water shortage *per se* as is shown by the results under irrigation. Despite the fact that abundant water is available and large top growth is made, alfalfa grown in dry regions under irrigation can be cut at much earlier stages without damaging the stand than in humid regions (Turpin, 1931; Dawson *et al.*, 1940; Staten *et al.*, 1945; Jackobs, 1950.) The most nearly complete study of photosynthesis in alfalfa available (Thomas and Hill, 1937a,b) is of irrigated alfalfa and shows more photosynthate going into root storage than into top growth, despite large yields. A factor here is that irrigated regions in general have cooler nights than humid areas, because of greater radiation. This should increase root storage because of decreased respiration, but it seems that other factors must also be operative.

### 4. *The Effect of Repeated Cuttings at Specified Stages on Root Reserves and Hay Yields in Current and Following Years*

A number of stage-of-harvesting experiments with alfalfa have included cuttings at certain stages of maturity throughout the season (Salmon *et al.*, 1925; Kiesselbach and Anderson, 1926; Graber *et al.*, 1927; Burlison *et al.*, 1930; Turpin, 1931; Griffith and Ramsey, 1932; Woodman *et al.*, 1933, 1934; Akers and Westover, 1934; Henson and Westover, 1935, 1939; Dawson *et al.*, 1940; Brown and Munsell, 1942; Weihing *et al.*, 1943; Nelson, 1944; Staten *et al.*, 1945; Carr, 1950). In the fall they often had remaining various amounts of growth which did not reach the specified stage. These were sometimes cut, sometimes not. Under humid conditions, what is done with this fall growth may affect the next year's yields more than the stage of cutting followed previously. The results of some experiments are partly vitiated by this failure to realize the vital significance of the date of the last cutting. This is not true under irrigation (Jackobs, 1950).

Under irrigation, the total yield of cuttings at one-tenth bloom is always, and the total of cuttings at bud stage is often, equal to the total yield of fewer cuttings of lower quality hay at later stages. Therefore, there is no reason under irrigation for cutting later than one-tenth bloom and bud stage cutting is often profitable.

Under humid conditions the stage giving greatest root reserves and longevity of the stand is nearly or quite the full bloom stage. Because of the low quality hay resulting from this stage of cutting, the stage almost universally recommended in humid regions is early bloom: generally one-tenth bloom in the drier areas, or one-fourth to one-half bloom in more humid regions.

Repeated cutting at bud stage or before has been uniformly disastrous in humid regions. This was true even in tropical Hawaii, where growth is essentially continuous (Wilsie and Takahashi, 1937). Bud stage cutting did not weaken dry land alfalfa in South Dakota (Hume *et al.*, 1937).

### 5. *How Many Cuttings a Year?*

In planning cutting systems for a region, the average growing season may be just right, too long, or too short for a definite number of cuttings at a predetermined stage. For example, along parallel 40° east of the 95th meridian, the season is of about the right length to make three cuttings a year, and to provide abundant fall growth.

North of this, centered on about parallel 43°, is a region in which the season is too long for two cuttings of good quality, but too short for three cuttings at stages which will uniformly maintain a strong stand. This had led to conflicts in recommendations between those who considered maintaining the stand all important, and those who cut for good quality hay and accepted the chance of injuring the stand.

A desirable compromise here, often, is to make two cuttings in the first cutting year and three in the second and third. Certainly young stands should be given every opportunity to grow strong. Another plan is to make three cuttings in dry seasons, two in wet. On soils basically not adapted to alfalfa fewer cuttings should be made than might be justified on adapted soils (Bachtell *et al.*, 1946).

Where a large share of the year's yield is harvested in a coarse first cutting it may be desirable in well-established alfalfa to make the first cutting early, and to restore root reserves by another cutting later.

When the season is long enough for more than three cuttings, seasonal and farm management effects will often prevent carrying out plans for definite numbers of cuttings, but a safe date for the last cutting must be adhered to and, as this date is approached, crops must be cut or left as may be indicated.

Under irrigation, the injury from a single early cutting is so slight that these problems hardly exist, except that continued pre-bud cutting is injurious.

## IV. The Relation of Various Factors to the Time of Cutting

### 1. *Indicators of Stage of Maturity*

In humid regions, especially with the common alfalfas, the bloom often partly or entirely fails, so that "¼ bloom," "½ bloom," "full bloom" are by no means as definite as one could wish, and it is desirable to have other indicators. Joseph E. Wing (1916), who perhaps did more than any other man to introduce alfalfa in the eastern states, recommended cutting when the shoots for the next crop appear at the crowns, and from 1905 to 1925 almost no other rule for cutting alfalfa was given. It was also stated that alfalfa would be severely damaged if the crown shoots were allowed to grow tall enough to be cut by the mower in harvesting the crop. The Wisconsin Agricultural Experiment Station (Moore and Graber, 1922, 1925) was the first to show that this had no basis in fact and many have since confirmed this conclusion (Salmon *et al.*, 1925; Willard *et al.*, 1934; Tysdal and Westover, 1949). The beginner who does not know when his alfalfa should be cut will not often be helped by looking for shoots at the crown. (See Section IV 2.)

The slowing up of growth with maturity is obvious to the grower who watches his crop and is in itself a good indicator of time to cut (Wing, 1916, p. 293). Diseases and insects are likely to cause a slight yellowing of the field at the same time (Tysdal and Westover, 1949). Even though there is no visible bloom, flower branches are always present and indicate the period.

Since alfalfa bloom in the first cutting tends to come at the same time each year, dates of cutting (Willard *et al.*, 1934; Weihing *et al.*, 1943; Burlison *et al.*, 1943) become as accurate as any other single indicator of when to make the first cutting and are very helpful for others, especially if not more than three cuttings are to be made. With more than three cuttings, seasonal effects so often prevent following a schedule as to reduce the value of recommended dates. From an extension viewpoint, dates have the great advantage of being definite and not subject to the subjective difficulties of estimating a stage of bloom or of finding shoots at the crown.

### 2. *Shoots at the Crown*

Alfalfa generally develops buds and, later, shoots at the crown as it matures. The development of these buds into shoots has long been given as a sign that the field is ready to cut. (See Section IV, 1.) The difficulty is that in humid areas it is very seldom that they appear at one time uniformly and generally, as would be necessary for their successful use as a cutting indicator. Many times the writer has found new shoots before bloom, as Burlison *et al.* (1930) evidently found, since their ''first shoots'' stage averaged considerably earlier than one-tenth bloom. Salmon *et al.* (1925) and Kiesselbach and Anderson (1926) on the other hand, place the ''new growth'' stage at or just after the one-tenth bloom stage.

Several factors affect the development of these shoots (Willard *et al.*, 1934). During the growing season more vigorous buds and shoots will develop in seasons favorable for high root reserves. On the other hand, almost no buds will start into growth in dry weather, so that the new growth rule breaks down entirely at the very time when early cutting can be done without injury. When a heavy rain breaks a prolonged drought, there is prompt and vigorous growth of shoots. In wet weather light favors the growth of shoots. Crowns exposed to the sun by lodging may have shoots 10-12 in. long when those of adjacent erect alfalfa have none.

Grandfield (1943) made a study of the development of the crown buds in the fall and showed that any cutting system which depletes root reserves decreased the number of crown buds.

### *3. Leafhoppers*

The potato leafhopper (*Empoasca fabae,* Harris) was shown by Jones and Granovsky (1927) to damage alfalfa seriously. Since that time it has been studied by many workers (Granovsky, 1928; Jewett, 1929, 1934; Monteith and Hollowell, 1929; Smith and Poos, 1931; Poos and Westover, 1934; Willard *et al.*, 1934; Johnson, 1934; Searls, 1934, 1935; Graber and Sprague, 1935; Poos, 1942).

Leafhoppers cause yellowing of the crop, lower percentages of protein and carotene in the hay, and stunting and weakening of the stand of alfalfa. They are perhaps the most important single insect pest of alfalfa in the eastern half of the United States. They do not affect the first cutting appreciably, because they do not appear until it is nearly mature. A result of leafhopper attacks in the Corn Belt is that the second cutting, with a higher percentage of leaves than the first cutting at corresponding stages, usually does not have a higher protein content than the first cutting at corresponding stages.

In Wisconsin, late cutting of the first crop, after the eggs for a second brood have been laid in it, has been reported as an almost complete practical control of the insect in the second cutting (Graber and Sprague, 1935; Searls, 1934, 1935). In the central Corn Belt and east this is not the case (Willard *et al.*, 1934; Poos and Westover, 1934). Injury to the second crop is the same at the same age, whenever the first cutting is made, so that leafhopper damage in the second crop cannot be controlled by cutting schedules in that area. However, leafhopper injury to the third crop in that region is sometimes reduced by late cutting of the second crop, (Jewett, 1934; Willard *et al.*, 1934) in much the same way as reported between the first and second crops in Wisconsin.

### *4. Can Fertilizers Prevent the Bad Results of Early and Frequent Cutting?*

Fertilizers cannot compensate for lack of photosynthates. Brown and Munsell (1942) say: "An inspection of the data . . . leaves no doubt that liberal fertilization has *not* prevented the harmful effects of certain cutting systems" (specifically, three early cuttings in one year). All other observations support this conclusion, though plots well fertilized with minerals have had *slightly* better stands under all cutting treatments than those not so fertilized.

### 5. *Varieties*

There has been little difference in the response of adapted varieties of alfalfa to cutting schedules (Brown and Munsell, 1942; Willard, 1950). Alfalfa breeding nurseries are universally cut uniformly, and it is rare for a variety to indicate that a different cutting schedule might have given better results. An exception is Ladak, which is so extremely different in its habit of growth from the common alfalfas that a different cutting schedule may be required for best results (Tysdal and Kiesselbach, 1939).

### 6. *Which Cutting Is of Highest Quality?*

In the Corn Belt and similar climates, including England and western Europe, the first cutting makes up a considerable share of the year's yields. The percentage of leaves and protein in the hay is definitely higher in the later cuttings at the same relative stages than in the first, and the last cutting is much the best. In irrigated regions, this is not true. In fact Headley (1942) reports the value for beef cattle as consistently in the order first, third, second, with no very large differences. Sotola's (1927) summary, largely from irrigated regions, showed no large differences between cuttings. Conditions of growth, rather than any necessary difference between cuttings made at different times in the season, will determine the quality of a given cutting.

### 7. *Market Grade of Hay*

Since the federal hay grades are based on leafiness, color, and foreign material in hay that is properly cured, there will always be a high correlation between time of cutting and the federal grade of the hay, the earlier cuttings being of higher grade. The correlation is greater in humid areas, where insect and disease attacks reduce the color of alfalfa even before it is cut, than under irrigation.

### 8. *Modifying the Time of the First Cutting by Spring Clipping*

In regions where the first cutting is heavy and comes at an unfavorable time for getting the work done, the suggestion has been made to pasture heavily early or to clip the very early growth in the spring in order to delay the first cutting (Wisconsin Agr. Expt. Sta. 1942; Graber and Burcalow, 1943; Jackobs, 1950). The first cutting can be delayed one to two weeks by clipping the first growth when it is 4 to 12 in. high, thus lengthening the cutting season and permitting continued operation of dehydrators or better distribution of haying and other farm labor.

The yield for the season is slightly reduced under irrigation, and in humid regions by amounts up to 25 per cent or more, even to stand destruction, in weak stands. In humid regions, spring clipping or grazing should not be done except on healthy vigorous stands in which abundant root reserves have been accumulated, and the later cuttings should be regulated to reestablish high reserves.

### 9. *Bacterial Wilt*

Bacterial wilt develops best when the plants are weakened and has repeatedly been shown to affect frequently-cut areas more seriously than those less frequently cut (Jones, 1940). Consequently alfalfa breeders use early and frequent cutting as a tool in the early evaluation of wilt-resistant strains (Smith and Graber, 1941).

### 10. *Height of Cutting*

The new growth of alfalfa starts from crown buds most of which are at or below the surface of the ground. Consequently, height of cutting is not an important factor in recovery after cutting (Willard *et al.*, 1934). It is sometimes recommended to clip new seedings high. This seems unnecessary and undesirable (Thatcher *et al.*, 1937; Agronomy Department, Ohio Agr. Expt. Station, 1938, p. 48). The basic reason for clipping new seedings is to control annual weeds. These are the more effectively controlled the lower they are cut. Alfalfa recovers in the seeding year exactly as it does in later years, and to clip new seedings high is to favor the weeds instead of the alfalfa.

Harrison (1939) and Hildebrand and Harrison (1939) made greenhouse studies of heights of cutting ranging from 1 to 6 in. in simulated pasturing at different heights, but the results do not have application to haymaking.

### 11. *Percentage of Dry Matter in the Green Plants*

An advantage sometimes suggested for late cutting of alfalfa is that the hay is easier to cure, because it contains less moisture when cut. From bud stage to seed stage there is an increase in the per cent of dry matter from a minimum in humid climates of about 14 per cent at pre-bud stages to a maximum in dry climates of about 40 per cent at the seed stage. The average difference in percentage of dry matter between early bloom and late bloom will usually be about 7 to 8 per cent, rising from about 20 to 28 per cent. Since under ordinary curing conditions alfalfa immediately after cutting will evaporate 5 to 15 per cent of water in two hours, this difference is not of too much practical importance

(Salmon *et al.*, 1925; Kiesselbach and Anderson, 1926; Woodman *et al.*, 1933; Willard *et al.*, 1934).

The hygroscopic quality of very early cut hay (Dexter *et al.*, 1946; Dawson and Musgrave, 1950) is the important reason why hay cut in the bud stage or earlier in humid climates and cured by ordinary curing methods will almost certainly spoil.

### *12. Alfalfa-Grass Mixtures*

Since in any profitable alfalfa-grass mixture the alfalfa is the more important constituent, it would be anticipated that such mixtures would react to different stages of cutting much as alfalfa itself does. Grasses endure frequent cutting so much better than alfalfa that early and frequent cutting for the region quickly reduces the percentage of alfalfa in the mixture. If the grass is a strongly competitive one, early cutting adds to the severity of the competition. The hay yield of timothy or other late maturing grasses may be reduced if a timothy-alfalfa mixture is cut at the best stage for the alfalfa, but the quality of the hay is correspondingly increased. In practice, most alfalfa-grass mixtures for hay may be cut if they were pure alfalfa (Bachtell *et al.*, 1946; Comstock and Law, 1948; Dotzenko and Ahlgren, 1950).

## V. SUMMARY OF PRACTICAL RECOMMENDATIONS FOR CUTTING ALFALFA

As any crop of alfalfa matures, the yield increases to approximately the full bloom stage, the percentages of protein and of carotene decrease rather regularly, and the protein and carotene per acre reach a maximum at about the early bloom stage.

When several successive cuttings are made at too early a stage of growth, the stand will be injured. Under humid conditions, maximum vigor of stand cannot be maintained by cutting continuously earlier than full bloom. Under irrigation, continued cutting at bud to early bloom stage is feasible. In grassland climates, or in dry seasons in more humid climates, continued medium early bloom cutting will not injure the stand.

Early cutting injures the stand through preventing adequate storage of reserve materials in the roots, which takes place as the crop matures, if the plants are healthy. In humid climates this storage is favored by dry weather, so that a given cutting system is much less severe in a dry season than in a wet one.

Another period of active storage is in the fall, during the last seven to ten weeks before winter freeze-up. If alfalfa is cut or pastured during this period root storage is prevented and new growth prevents hardening of the alfalfa, so that it is more susceptible to winterkilling and yields less the next year. This injury is greater as the last cutting is made later until about three weeks before freeze-up. If cut just before freeze-up, so that no new growth starts, the injury is less, but this is hard to do. The injury from late cutting is much less important under irrigation.

In any humid area, two dates of great practical importance to the alfalfa grower can be set—the average date of making the first cutting and the average date after which the last cutting should not be made. Both of these, obviously, are subject to weather changes, especially related to dry and wet seasons. The latest date in the fall is basic to any planning for alfalfa management in humid regions.

## VI. Cultivation of Established Alfalfa

The early writers on alfalfa (Wing, 1916, and many others) recommended the regular use of a disk, or, preferably, a narrow-toothed springtooth harrow, on the stand to keep out weeds, especially bluegrass, and to conserve moisture. Considering the universality of this recommendation, it is not surprising that many experiments have been conducted to check on it (Kiesselbach and Anderson, 1926; Burlison *et al.*, 1930; Etheridge and Helm, 1933; Akers and Westover, 1934; Willard *et al.*, 1934; Henson and Westover, 1939; Weihing *et al.*, 1943; Staten *et al.*, 1945; Garver, 1946).

Of these investigators, only Etheridge and Helm (1933) found a significant increase in hay yields from regular cultivation. In this three-year test, the cultivated alfalfa outyielded the uncultivated, the hay from the cultivated plots contained almost no weeds, and at the end of the third year the soil area still occupied by alfalfa averaged 90 per cent where cultivated, 45 per cent where not cultivated, with yields of pure alfalfa hay in about the same ratio. They recommended two harrowings a year with a half-round springtooth harrow at once after the second and third cuttings of hay.

In the other tests, the best result was that cultivation did no harm and, in some instances, produced cleaner hay. Where a disk was used, or in tests since bacterial wilt became an important factor in alfalfa culture, there was always a loss from the practice. Etheridge and Helm (1945) still recommend the practice for alfalfa hay production; no other recent bulletin recommends it, except for special circumstances, such as to precede seed production in old thin stands (Tysdal and Kiesselbach, 1941), to break up crusts left by silty irrigation water, pasturing, or other abuses of irrigated land (Tysdal and Westover, 1949), to sow grass in old thin stands (Willard, 1936), to expose grasshopper eggs (Garver, 1946), to cross-cultivate alfalfa in rows (Garver, 1946), or to eradicate winter annuals such as downy brome (Grandfield and Throckmorton, 1945).

Where cultivation for any special uses is indicated, a springtooth harrow, preferably with special narrow rounded teeth, should be used—never a disk. Least harm is done by cultivating in early spring (Garver, 1946), but this is not often feasible east of the Missouri River. Late fall cultivating may be practical for eradicating winter annuals.

## VII. OTHER WEED CONTROL METHODS IN ALFALFA

Alfalfa has an excellent reputation for smothering out weeds. One of the most commonly given and practically valuable methods for controlling Canada thistle in the Corn Belt is to establish vigorous alfalfa over it. If alfalfa is to control weeds, however, it must be cut to maintain vigor. One of the first signs of destructive cutting is the appearance of many weeds in the field, especially annual grasses.

However, there are weeds which appear in alfalfa regardless of the method of cutting simply because their time of establishment coincides with the time when alfalfa is going into winter dormancy. Consequently, even though it makes a vigorous growth it does not make a tall enough growth to shade out winter annuals which start after the last cutting of the season. South of parallel 40°, the first cutting of both old stands and new seedings of alfalfa is likely to include a high percentage of these winter annuals in the hay. Downy brome (*Bromus tectorum*), cheat (*Bromus secalinus*) and other winter annual bromes, foxtail barley (*Hordeum jubatum*), daisy fleabane (*Erigeron annuus* and *ramosus*), bitter winter cress (*Barbarea barbarea*), field peppergrass (*Lepidium campestre*), chickweed (*Alsine media*), and many others are in this group. No practical cutting system will eliminate them.

In California (Crafts, 1947; Raynor, 1947) oils reinforced with dinitro compounds or pentachlorophenol have been used in the winter to take weeds, especially grasses, out of dormant alfalfa. The top growth of the alfalfa is killed but recovers readily from the crown; the weeds do not. There is a wide field for similar applications in the East. Dr. Warren C. Shaw (personal communication to the writer) writes of taking cornflower (*Centaurea cyanus*) and chickweed out of a new stand of alfalfa with the triethanolamine salt of dinitro-*o-sec.* butyl phenol.

The writer has taken chickweed out of established alfalfa without injury by the use of 15 to 20 lb. of sodium chlorate per acre, applied in at least 80 gallons of water early in the spring before the alfalfa has made much growth.

Several recent experimenters (Viehmeyer *et al.*, 1950; Watson, 1950; Peters and Willard, unpublished) have taken annual and perennial grasses out of alfalfa with trichloracetate (TCA), and the treatment looks promising. Alfalfa endures considerably more TCA than grasses, though not entirely wthout injury. The degree of injury under different conditions and the economics of the operation require further investigation, before recommendations can be made.

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# Soil Potassium

R. F. REITEMEIER
*U.S. Department of Agriculture, Beltsville, Maryland*

CONTENTS

*Page*
I. Introduction . . . . . . . . . . . . . . . . . . . . . . . . 113
II. Forms of Soil Potassium and Their Availability to Plants . . . . . . 114
  1. Soluble Form . . . . . . . . . . . . . . . . . . . . 115
  2. Exchangeable Form . . . . . . . . . . . . . . . . . . 116
  3. Primary Mineral Forms and the Release of Nonexchangeable Potassium . . . . . . . . . . . . . . . . . . . . . . 119
    a. Release from Primary Minerals . . . . . . . . . . . . 119
    b. Release from Soils . . . . . . . . . . . . . . . . 123
  4. Clay Mineral Forms . . . . . . . . . . . . . . . . . 131
    a. Original Potassium Content . . . . . . . . . . . . 133
    b. Difficultly Exchangeable Potassium by Fixation . . . . . . 135
  5. Relationships and Equilibria among the Various Forms . . . . 141
III. Influence of Other Cations on Forms of Soil Potassium . . . . . . . 143
  1. Calcium and Hydrogen . . . . . . . . . . . . . . . . . 143
    a. Soluble and Exchangeable Forms of Potassium . . . . . . 144
    b. Release of Nonexchangeable Potassium . . . . . . . . . 149
    c. Fixation of Potassium in Nonexchangeable Form . . . . . 149
    d. Potassium Relationships of Naturally Calcareous Soils . . . 150
  2. Ammonium Fixation and Its Relation to Potassium Fixation . . . 151
IV. Relationships of Soil Microorganisms to Soil Potassium . . . . . . 153
  1. Release of Nonexchangeable Potassium . . . . . . . . . . 153
  2. Fixation of Potassium in Microbial Protoplasm . . . . . . . 154
V. Effect of Aeration and Compaction on Availability of Potassium . . . 155
VI. Movement and Distribution of Potassium in the Soil Profile . . . . 156
  1. Effect of Soil and Fertilizer Characteristics . . . . . . . . 157
  2. Effect of Plant Growth . . . . . . . . . . . . . . . . 158
VII. Epilogue . . . . . . . . . . . . . . . . . . . . . . . . 159
References . . . . . . . . . . . . . . . . . . . . . . . . 159

## I. INTRODUCTION

Although in the form of the simpler chemical compounds it is one of the most soluble elements, in the soil-plant system potassium behaves with extreme differences of solubility and mobility. Thus, its absorption from solutions and soils is highly efficient, its movement through the plant very rapid, yet its net retention in individual living cells may be quite strong, and some of the bonds persist until death of the cell. Soil potassium ranges from the soluble state through states of decreasing mobility to that of an essential constituent of certain primary minerals from which it is released only by destruction of the crystal structure. In many soils the entire range of known forms of potassium occurs; in other soils some forms may be lacking, usually because of the absence of some types of primary or clay minerals. The complex behavior of potassium in soils and plants has been succinctly epitomized by Albrecht (1943) as follows: "Because of the prevalence of its minerals in the lithosphere, of its readily soluble nature, of its readiness to become insoluble and inexchangeable from the colloid, of its movement from vegetation to the soil through leaching from the tops or exchange from the roots, and of its reserve in the silt and sand minerals to buffer the clay, potassium is so nomadic that its performances in any particular situation are difficult to interpret."

## II. Forms of Soil Potassium and Their Availability to Plants

Of the major and secondary nutrient elements, potassium is usually the most abundant in soils. However, the range of total potassium contents which occur in soils is enormous. As an extreme example of this over a relatively short geographical distance, Marbut (1935) reported the $K_2O$ content of the A horizon of Durham sandy loam at Stone Mountain, Georgia, to be 5.15 per cent and that of the $A_1$ and $A_2$ horizons of Tifton fine sandy loam in Randolph County, of the same state, to be only a trace. These values are unusual for both the high and low levels, and the bulk of values will lie somewhere between them.

In soils which have not had potash applications, the proportion of the total potassium held in soluble and exchangeable forms usually is relatively small. The majority of it resides in potassium-bearing primary and clay minerals. The high potassium primary silicate minerals are muscovite, biotite, orthoclase, and microcline; but other micas, feldspars, and other minerals may contain substantial amounts of potassium. Of the clay minerals, the illite group (as currently recommended, this term includes the entire range of hydrous micas) is considered to be the only one having a substantial potassium content. Alexander, Hendricks, and Nelson (1939) determined that the $<0.3$-$\mu$ clay of a Miami $B_2$ horizon, which is largely hydrous mica, had a $K_2O$ content of 4.37 per cent, while that of a Greenville $B_2$ horizon, in which hydrous mica was not detected, contained only 0.07 per cent. Pennington (1949) reported the $<0.08\ \mu$ fraction of a Houston B horizon to contain 0.56 per cent K and the mineral composition to be 80 per cent montmorillonite, 20 per cent hydrous mica intermediates, and no illite.

The various forms of soil potassium generally are related and comprise a system in which an increase in one form occurs at the expense of one or more other forms and in which the net movement may occur from less available to highly available states, or the reverse, depending on the particular stress. The availability to plants depends on the amount and relative mobility of the different forms, including the rate of replenishment of depleted immediately available forms by reserve supplies.

### 1. *Soluble Form*

Although soluble potassium is invariably present, appreciable quantities are not likely to occur except by application of soluble potash fertilizers, from irrigation water of high potassium content or in soils naturally high in mixed soluble salts, including those of potassium. For this purpose ''soluble'' is defined as the quantity existing at any one time dissolved in water of a soil under normal field moisture conditions and relatively unbound by cation exchange forces. The distinction between this form and several others is necessarily arbitrary, as by mere dilution with water, the soluble potassium will increase because of hydrolysis of exchangeable potassium, further replacement of exchangeable potassium by divalent ions, or dissolution of potassium-bearing minerals (Reitemeier, 1946). The displaced soil solutions of a number of humid area soil samples studied by Anderson, Keyes, and Cromer (1942) contained between 1 and 10 p. p. m. of $K_2O$ on the soil basis; on increasing the water content to a soil : water ratio of 1 : 10, the extracted potassium increased by 3- to 27-fold. The potassium content of the soil solution represented from 0.5 to 7.8 per cent of the exchangeable plus soluble value. Lachower (1940) determined exchangeable potassium and soluble potassium at a 1 : 5 soil to water ratio for five irrigated and fertilized soil samples; the soluble portion constituted from 19 to 33 per cent of the exchangeable plus soluble fraction. For non-saline soils, the soluble potassium is usually included in the exchangeable fraction as determined by a salt or acid extraction.

The amount of soluble potassium, even in fertile soils, is inadequate to meet the major part of the requirements of a crop. Apart from the concept of contact feeding by roots on exchangeable cations (Jenny and Overstreet, 1939), it is presumed that all potassium entering roots must be in the soluble form. However, the replenishment of soluble potassium may occur sufficiently rapidly directly from the exchangeable form and indirectly from the nonexchangeable form to satisfy plant demands. During the course of a cropping season the levels of all three may drop together to differing degrees. Hoagland and Martin (1933) grew tomatoes on a series of samples of Vina clay loam treated with different amounts of potassium salts; the p. p. m. of potassium soluble at 50 per cent water content decreased as a result of plant uptake as follows: 5.4 to 0.8, 11.0 to 4.0, 2.2 to 0.6, 3.2 to 0.7, 2.0 to 0.5, 2.8 to 0.4, 3.2 to 0.3, and 6.1 to 1.0. The current prevailing attitude toward the importance of soluble soil potassium in immediate availability is to ignore it in favor of the principles of contact exchange and of complete availability of exchangeable potassium. It is of interest that recently York (1949), although recognizing the importance of the soluble-exchangeable equilibrium, concluded that the controlling factor in potassium absorption is the available supply in the soil solution.

### 2. *Exchangeable Form*

The exchangeable potassium of a soil is difficult to define theoretically and to determine experimentally, for at least three reasons: (*a*) the absence of a sharp distinction between soluble and exchangeable fractions, (*b*) the existence in some soils of difficultly exchangeable potassium which is not immediately extractable by the usual reagents, and (*c*) the dissolution of mineral potassium by the exchange extractant. In practice the determined exchangeable potassium value is almost certain to be affected by one or more of these factors.

The partition of potassium between soluble and immediately exchangeable forms depends on several factors including (*a*) the concentration of soluble potassium, (*b*) the nature and concentration of competing cations, and (*c*) the nature of the exchange material. The exchange adsorption of calcium and magnesium relative to that of sodium and potassium is increased upon dilution of the system with water. Thus, in a neutral soil having soluble calcium and potassium, dilution will effect an increase in exchangeable calcium and an equivalent decrease in exchangeable potassium. For two soils, and illite and kaolinite, Melsted and Bray (1947) found the exchangeable potassium to exceed calcium and magnesium at concentrations of 0.25 $N$ and 1 $N$; at lower salt contents, the reverse was obtained. Brown and Parks* found that within a series of total salt concentrations of 0.01, 0.1, and 1 $N$, divided equally between calcium and potassium chlorides, Caribou loam and Clyde silty clay loam adsorbed relatively more potassium and less calcium with increasing salt concentration. After removal of organic matter from the two soils, the effect was so accentuated that at 1 $N$ concentration, the exchangeable potassium content was three times that of calcium. This trend was obtained also for K-H systems, i.e., relative to potassium, hydrogen acted similarly to calcium.

* The use of an asterisk throughout this article refers to unpublished data of the Bureau of Plant Industry, Soils and Agricultural Engineering.

Schachtschabel (1940) made extensive investigations of the relative replacing abilities of different cations on a variety of cation exchange minerals. With increasing chloride salt concentration, potassium became more effective than the alkaline earth cations in replacing ammonium from $NH_4$-montmorillonite and $NH_4$-kaolinite. In the case of $NH_4$-muscovite, potassium (also rubidium and cesium) was more effective even at the lowest concentration studied; $NH_4$-feldspar behaved similarly to mica. From equivalent mixtures of calcium and ammonium acetates, mica preferentially adsorbed ammonium over calcium in the ratio 94 : 6; contrariwise, humic acid adsorbed the two ions in the ratio 8 : 92. It was concluded that calcium ions are bound preferentially by humus, potassium and ammonium by mica, and that montmorillonite binds all three ions about equally. It is well established that potassium and ammonium behave closely similarly both in immediately reversible exchange reactions and in the fixation of cations in difficultly exchangeable forms. The ammonium-saturated minerals used by Schachtschabel were dried prior to addition of the competing cation. Because drying is known to increase fixation of ammonium and potassium by montmorillonite and micaceous minerals, Marshall (1949) has proposed this as an explanation of the fact that the order of replacing abilities of the cations, observed by Schachtschabel (1940), differs considerably from the lyotropic series established by other workers on undried clays. Charriou (1924) found that from a mixture of $KHCO_3$ and $Ca(HCO_3)_2$ in equal concentrations, humic acid adsorbed Ca but not K.

At various times different workers have ascribed the role of immediate availability of potassium to primary potassium-bearing minerals, soluble, and exchangeable forms. Nostitz (1922) treated ammonium-saturated soils with Ca + Mg and Ca + Mg + K mixtures. Where K was restored to its original value, plants grew about as well as on the original soil, but where it was not returned to the soil, poor germination, K-deficiency symptoms, and early death resulted. It was concluded that in the estimation of fertilizer requirements the exchangeable potassium should be considered. However, Gedroiz (1931) assumed that the plant had to rely almost entirely on nonexchangeable sources. It can be presumed that the chernozem soil he used exhibited a high rate of release of nonexchangeable to exchangeable forms. According to Stoliarova (1940) the available K of podsols and red earths is primarily the exchangeable form, while on chernozems plants use mainly nonexchangeable K.

The recent tendency to regard exchangeable and available potassium as synonymous or practically identical is subject to doubt on a number of grounds, all of which may not apply to any particular soil. It is not difficult to arrive at the opposite conclusion; namely, that except by chance balancing of opposing factors, the determined exchangeable potassium never corresponds exactly with the available. These considerations include the following: (*a*) the inability of a plant to remove completely the exchangeable potassium—even after prolonged intensive cropping a soil will contain an average minimum exchange level characteristic of the soil, kind of plant, plant population, root density, etc. (Ayres, 1949; Ayres, Takahashi, and Kanehiro, 1947; Chandler, Peech, and Chang, 1945; Hoagland and Martin, 1933; Reitemeier, Brown, and Holmes;* Schachtschabel, 1937); (*b*) the usual inclusion of soluble potassium in the exchange extraction; (*c*) the release of nonexchangeable potassium of primary and clay minerals; (*d*) fixation into difficultly exchangeable forms during the cropping period (Bartholomew and Janssen, 1931; Hoagland and Martin, 1935); and (*e*) specific differences among the abilities of plants to utilize exchangeable or nonexchangeable potassium, or both, (Drake and Scarseth, 1940; Lewis and Eisenmenger, 1948; Tyner, 1935).

In an examination of the response of cotton on a large number of Alabama soils, Volk (1942) concluded that predictions as to the need for a second 25 lb. $K_2O$ increment partly on the basis of exchange level were unreliable in 35 per cent of the cases. He attributed differences in response to such factors as native available nutrients, subsoil compaction, subsoil nutrients, organic matter, and previous cultural practices. Despite the many theoretical and actual obstacles besetting the use of exchangeable as a measure of available potassium, correlations of moderate precision have been found between exchangeable potassium and the potassium content of plants. Thus, linear relationships between the potassium content of plants expressed as per cent K and the logarithm of the exchangeable K value were found for tobacco by Attoe (1946), for oats by Attoe (1949), and for alfalfa by Seay, Attoe, and Truog (1950). Bray (1948) currently regards the exchangeable form as the only important source of seasonally available potassium of cornbelt soils, even those of Illinois which are known to have relatively high rates of release of nonexchangeable potassium.

Usually, the degree of saturation of the cation exchange complex by K is small, yet the availability of the exchangeable K is relatively high. Jarusov (1937) concluded that a decrease in saturation of an ion of low energy of adsorption, e.g., K in presence of Ca or H, will not be accompanied by a drastic drop in its mobility and availability. Marshall (1944) indicated that although for a large cation exchange the replacement of two cations is in direct ratio to their exchangeable contents, for a small exchange the relative release depends on their activities. The ratio of the magnitudes of the activities of exchangeable K and Ca ions at equal concentrations is about 10:1. He would expect lower K:Ca ratios in plants grown in nutrient solutions rather than in soils because of the much smaller dissociation of soil Ca relative to that of K. The relative "absorption coefficients" of cations by plants were presumed by Van Itallie (1938) to be as follows: Ca-1, Mg-2, Na-10, and K-20.

### *3. Primary Mineral Forms and the Release of Nonexchangeable Potassium*

By definition, all of the soil potassium except the soluble and immediately exchangeable forms is included in the term "nonexchangeable." The term "difficultly exchangeable" is applied to that which is more slowly released by the usual exchange extractants, or dependent for replacement on a particular cation or group of cations, or more or less quickly released by more vigorous extractants. Terms such as "moderately available," "slowly available," and "unavailable" refer to vegetation systems, and since the range of conditions is extremely broad, these terms are more vague. To be most informative, results should be accompanied by a statement of the methods used.

The potassium relationships of (*a*) sandy soils of very low content of clay mineral and primary potassium-bearing silicate minerals, and (*b*) predominantly organic soils such as peats and mucks, generally are less complex than those of other soils and the following discussion may not concern these two groups to any appreciable extent.

The weathering and decomposition of silicate minerals has been extensively studied by mineralogists, chemists, and soil scientists. Because many of these investigations have been made for geological rather than soil purposes, their application to soil conditions is doubtful. Most of the studies of release of nonexchangeable potassium have been made on soils of unknown mineral composition. However, information exists that the minerals of both the clay-size fractions and the larger size fractions may liberate potassium. Discussion of release of nonexchangeable potassium in this section therefore does not necessarily imply that only the primary minerals, and not the clay minerals, are important in this regard.

*a. Release From Primary Minerals.* A century ago Magnus (1848) grew barley on artificial soil having ground feldspar as the only source of potassium and obtained matured grain. An experimental defect of many such experiments on powdered minerals with regard to the release of nonexchangeable potassium is the failure to remove soluble and exchangeable cations following grinding. The process of grinding not only increases the exchangeable and soluble potassium by an increase in exterior surface, but extreme grinding may also modify the crystal structure sufficiently to destroy its characteristic properties (Jackson and Truog, 1940).

High potash micas and feldspars invariably liberate potassium to plants and extractants to some extent. Hartwell and Pember (1908) grew wheat in water cultures containing a 9.09 per cent $K_2O$-feldspar ground to less than 200 mesh. In the first water-culture crop, the growth was equal to that with 32 p. p. m. of potassium in solution, but in a replanting with the same feldspar sample, the growth was only 79 per cent of that of the complete nutrient solution.

Tyner (1935) grew corn, rape, buckwheat, alfalfa, alsike clover, peas, sorghum, Sudan grass, soybeans, oats, red clover and sweet clover in sand cultures comparing powdered microcline with KCl as the source of potassium. The efficient feeders on the feldspar potassium were alfalfa, alsike clover, red clover, and sweet clover. It was concluded that the clovers, being slower growing plants, can utilize potassium from more dilute media. A flowing culture experiment indicated the minimum potassium concentration for good buckwheat growth to be three p. p. m., while that for red clover was one p. p. m. Lewis and Eisenmenger (1948) approached the problem of plant specificity on the basis of degree of plant development. Twenty-two seed plants, ranging in degree of development from larkspur to lettuce, were grown on Merrimac sandy loam with application of KCl or ground orthoclase, and the potassium content of the oven-dry plants was determined at harvest. The percentage gain in potassium from both the feldspar and KCl over that of the control tended to decrease as plants ascended from lower to higher development. The average percentage gain by the five lowest plants from feldspar was 75, that by the five highest plants 8; corresponding values for KCl were 123 and 66. This result was explained by the assumption that in earlier ages plants had to obtain their nutrients from unweathered rocks.

It would appear more pertinent to the present discussion to indicate comparisons of the availability from micas and feldspars. Prianischnikov and Doiarenko (1911) reported that in sand culture biotite and muscovite were better sources of potassium than orthoclase and microcline, with biotite the best of the four. Blanck (1912, 1913) found the decreasing order of availability for these four minerals in experiments with oats to be biotite, muscovite, orthoclase, and microcline. The two feldspars contributed but little potassium and produced little or no increase in weight. The removal of potassium from the micas was not accompanied by any observed change in the external appearance of the particles. In another comparison of the same four minerals, Plummer (1918) observed the same order of availability to oats, rye, cowpeas, and soybeans; $CO_2$-saturated water and calcium bicarbonate solution extracted two to four times as much potassium from the micas as from the feldspars. The same mineral order was found by Fraps (1921) in soil experiments with corn and sorghum. Similar results of plant experiments have been obtained by other workers.

McCaughey and Fry (1913) and Denison, Fry, and Gile (1929) examined the weathering stages of feldspars and micas occurring as soil constituents. Orthoclase may be extremely altered or of fresh appearance in young soils. Microcline was always in bright unaltered cleavage fragments showing no chemical alteration. The degree of mica alteration was related to particle size. Biotite tended to be altered more in mineral composition than muscovite by loss of K and Mg and relative gain in $Al_2O_3$ and water. The decrease in $K_2O$ content of weathered muscovite was very close in magnitude to the increase in $H_2O$ content; biotite tended to weather to a relatively stable product containing about 4 per cent $K_2O$. In both micas the degree of blurring of the interference figure was inversely related to the potash content.

Goldich (1938) proposed two sequences of rock weathering on the basis of increasing stability of minerals as follows: (*a*) olivine, augite, hornblende, biotite, K-feldspar, muscovite, quartz and (*b*) anorthite (Ca-plagioclase), albite (Na-feldspar), K-feldspar, muscovite, quartz. McClelland (1951) determined the release of cations from muscovite, biotite, phlogopite, microcline, anorthoclase, labradorite, albite, augite, hornblende, and olivine during contact with bentonite. With the exception of muscovite, the order in which the cations were released followed the stability series of Goldich (1938). Gorbunov (1940) explained the greater ease of release of potassium from mica over that from orthoclase on the basis of type of atomic bonding and crystal structure. In the micas the cleavage plane between the layers is the site of potassium ions which can be removed by cation exchange. In orthoclase the occurrence of covalent bonds and the location of potassium inside the crystal lattice hinder its release.

Barshad (1948) was able reversibly to transform vermiculite to "biotite" by treatment with potassium solutions at 70°C. and biotite to vermiculite by similar treatment with magnesium solutions. The only change in the composition appeared to involve a cation exchange between potassium and magnesium and the accompanying change in extent of hydration.

Caillere, Henin, and Guennelon (1949) reported a partial conversion of phlogopite (a high Mg biotite) into vermiculite by boiling in concentrated magnesium chloride solutions. Similar treatment of muscovite and illite with calcium chloride resulted in other minerals of expanded lattice. The hydration of mica particles upon weathering is regarded as mainly the result of replacement of potassium by calcium, magnesium, and hydrogen ions (Barshad, 1950). The interlayer hydration and lattice expansion are characteristic of the 2:1 type of crystal structure and depend on the interlayer cation. Cations as potassium and ammonium which produce a contracted lattice are thereby rendered difficultly exchangeable under ordinary soil conditions.

A natural transformation of biotite to vermiculite within a soil profile has been observed by Walker (1949). As the stage of weathering advanced, the biotite particles lost color and showed an increase in the C-axis spacing. The 14-Å spacing, characteristic of vermiculite, appeared at later stages. The process is visualized as at first a replacement of the more accessible potassium by magnesium, calcium, and water molecules. With further replacement toward the center of the flakes, the binding of the layers decreases and basal plane spacing increases. A mixed layer structure arises in which increasing numbers of layers are converted to the vermiculite type.

In a comparison of the response of cotton to potash additions, Plummer (1915) found the soil in which micas predominated to respond less than the one in which K-feldspars predominated. Most soils contain mixtures of both series of minerals. The abundance of the two and the stage of weathering of each will, of course, influence their relative contribution to the potassium supplying capacity. Goldschmidt and Johnson (1922) suggested that a soil's content of mica minerals should be valuable as a guide to the application of potash fertilizer. On the other hand, de Leenheer (1950) attributed the lack of response of crops to potash on some polder soils of Belgium to the presence of potassium feldspars. Glauconite, which occurs in greensand, greensand marl, and soils derived therefrom, can supply appreciable amounts of K to plants, especially when relatively abundant (Lipman and Blair, 1917; True and Geise, 1918).

Several studies have been made of the release of potassium from various size particles separated from soils. Graham (1943) measured the release of calcium, magnesium, and potassium from silt-size fractions of soils from seven states to soybeans during contact with H-clay. Some soils released all three nutrients; others calcium and magnesium, calcium only, or none. The Barnes (North Dakota) silt released potassium; Clarion (Iowa) and Hyrum (Utah) did not; with Putnam (Missouri), Lufkin (Mississippi), Hays (Kansas) and Cisne (Illinois) silts potassium moved instead from the seeds or plants to the clay surface.

Olsen and Shaw (1943) made Neubauer tests on 2-10, 10-20, and 20-50 μ silt fractions of Clermont, Wooster, and Brookston soils from which the exchangeable potassium had been removed. Significant amounts of potassium were removed from all fractions, but the amount released increased with decreasing particle size. Merwin (1950) compared the release abilities of sand, silt, and clay fractions of four New York soils during storage while saturated with various cations. The contributions of the fractions to total potassium release were as follows: sand 0-18 per cent, silt 15-51 per cent, and clay 40-83 per cent. No correlation was observed between the release by sand and silt fractions and their content of K-bearing minerals.

*b. Release From Soils.* It has long been known that the exchangeable and soluble potassium of a soil not receiving potash applications could not possibly be sufficient for the production of crops over substantial periods of time. Before the advent of the concept of base exchange in soils, the immediate source of potassium was understandably attributed to the breakdown of minerals. It is only comparatively recently that the interrelationships of exchangeable and released nonexchangeable potassium as they affect availability to plants have been extensively investigated.

Hopkins and Aumer (1915) extracted an Illinois soil with boiling HCl of specific gravity 1.115 for ten hours followed by addition of plant nutrients except potassium. After several unsuccessful attempts to grow red clover and rape, alsike and red clover finally made a start and were grown for a five-year period. Tops and roots were returned to the soil except for analytical samples. The later crops were equal to or larger than those on nonextracted soil. The average uptake of potassium from the insoluble residue by the crop was about 50 lb. per acre per year, which the authors attributed to release through the agency of decaying organic matter returned to the soil. Page and Williams (1925) calculated that crops had removed from certain no-potash plots over a period of time 900 lb. $K_2O$ per acre more than could be accounted for by the exchangeable potassium values. They assumed that the plants obtained this either from the deeper soil layers or from nonexchangeable reserves of the surface soil and were inclined to attribute it to the latter. Fraps (1929) observed the amount of potassium absorbed by experimental crops to be 3-16 times the reduction in water-soluble and 2-5 times the reduction in exchangeable potassium which occurred during cropping. According to Gedroiz (1931), when the exchangeable cations of a chernozem were replaced by calcium alone, oats and other crops grew as well without added potassium and magnesium as when they were added. He concluded that nonexchangeable supplies of the two ions were adequate for plant growth, but his assumption that this would be true of soils in general has not been justified.

A currently common method of measuring the relative release ability of different soils is that of prolonged cropping, either by successive cuttings of one planting of a certain crop, by repeated plantings of the same crop, or by a succession of different crops. A variety of experimental conditions, such as plant species, plant population, quantity of soil, effect of lime, and effect of potash additions, have been employed (Martin, 1929; Hoagland and Martin, 1933, 1935; Weissmann and Lehmann, 1934; Abel and Magistad, 1935; Schachtschabel, 1939; Bear, Prince, and Malcolm, 1944; Chandler, Peech, and Chang, 1945; Stewart and Volk, 1946; Ayres, Takahashi, and Kanehiro, 1947; Evans and Attoe, 1948; Reitemeier *et al.*, 1948; Ayres, 1949; Attoe, 1949; Gholston and Hoover, 1949; York, 1949; Breland, Bertramson, and Borland, 1950; Evans and Simon, 1950).

General principles of the release of nonexchangeable potassium during cropping which have emerged from these studies include the following: (*a*) broad differences exist among the capacities of different soils to supply nonexchangeable potassium of native origin; (*b*) soils of equal total potash content differ considerably in the availability of reserve potash; (*c*) fixed potassium is generally more available than native nonexchangeable forms; (*d*) although release from some soils occurs when the exchangeable potassium level is relatively high, it is more likely to occur at lower levels, provided the vigor of the plants is not drastically reduced thereby; (*e*) the initial level of exchangeable potassium is not an accurate index of reserve supplying power unless it represents the equilibrium level of the particular soil; (*f*) if the intensity and period of cropping is sufficient, the exchangeable potassium is reduced to a minimum value, and all subsequent release occurs at this exchange level —this is not as likely to occur in the field as in small containers; (*g*) plants absorb more reserve potassium than is liberated to the exchangeable form in the absence of plants during moist storage for the same period of time; (*h*) liming of an acid soil generally increases the extent of release.

The conditions which have been employed in prolonged cropping tests vary so widely that it is difficult to compare the results of one study with those of another. Many experiments of this nature serve mainly to rate the soils within a group studied at the same time under identical cropping and environmental conditions. Despite this limitation, it is of some interest to compare the ranges of values of release that have been obtained. A few cases are listed as examples, the release values expressed in terms of pounds of $K_2O$ per 2,000,000 lb. of soil: Ayres

(1949), 12 Hawaiian soils, 7 grass crops in 42 months, 325-1256; Bear, Prince, and Malcolm (1944), 20 New Jersey soils, 7 alfalfa cuttings in 1 year, maximum of 235; Chandler, Peech, and Chang (1945), 4 New York soils, 5 cuttings of ladino clover in 330 days, 19-441; Evans and Attoe (1948), 6 Wisconsin soils for 9 months, 4 oat crops, 27-82, 6 ladino clover cuttings, 34-129; Gholston and Hoover (1949), 8 Mississippi and 3 Alabama soils, 8 cuttings of German millet in 545 days, 151-697; Reitemeier *et al.* (1948), 14 soil samples from 5 states, 15 ladino clover cuttings in 740 days, 80-740; Stewart and Volk (1946), 10 Alabama soils, a variety of 12 crops during 5 years, 53-135. Some of the soils investigated in these studies contained fixed potassium in addition to the native nonexchangeable forms.

Schachtschabel (1937) explained the incomplete exhaustion of exchangeable and concurrent release of nonexchangeable potassium as due to increased rate of diffusion from within the crystal lattice because of the increase in concentration gradient due to the absorptive capacity of the roots. However, it appears that some soils release so little potassium at the minimum exchange level that the plants cannot survive, yet no further diminution of the exchangeable quantity occurs. Ayres (1949) expressed the idea that the minimum level represents an average value for a mass of soil and that the levels at root-soil contacts are relatively far below the average and maximum concentrations.

The Neubauer method, which has been widely used as a potassium availability test, often shows seedling uptake values that are close to the exchangeable values. Stewart (1929) established a correlation coefficient between Neubauer and exchange values of 0.9888, which indicated to him that exchangeable potassium determines the amount of potassium absorbed by seedlings. Bray (1948) states that the exchange values of cornbelt soils are closely equivalent to the Neubauer values, thus indicating no significant release from other forms during the growing season. However, Thornton (1937) compared the Neubauer and exchangeable potassium values for soil samples from eight Illinois experimental fields and found the Neubauer value to be appreciably higher in about one-half of the cases. Data of Lilleland (Hoagland and Martin, 1935) showed more available potassium in many California soils by the Neubauer test than by extraction with $NH_4$ acetate, 0.2 $N$ nitric acid, and similar extractants. Reuther (1941) found that for all but two samples of orchard soils, the Neubauer value exceeded the exchange value, in many cases substantially so. Wiessmann and Lehmann (1934) found large quantities of nonexchangeable potassium absorbed by Neubauer seedlings even in the first planting, and additional amounts were absorbed in two subsequent plantings. Some exchangeable potassium remained after each planting. This result was confirmed by Schachtschabel (1937) on eight soils with four or five seedling crops. Later (1939), he made Neubauer tests on the same group of soils using 25, 50, and 100 grams of soil. For the soils of high supplying capacity, the uptake on the basis of 100 grams of soil increased with decreasing weight of soil, while no appreciable increase occurred where the soil was of low supplying power. Reitemeier *et al.* (1948) noted some agreement between exchangeable and Neubauer values, but found that all the soils studied retained residual exchangeable potassium after the Neubauer cropping which, when added to the uptake, resulted in positive release values except for one soil. Subsequently, Reitemeier, Holmes, and Brown (1950) by reducing the Neubauer soil weight from 100 to 25 grams for a group of soils from the Great Plains increased the magnitude of the release value and the differential between soil samples. For many soils, therefore, release of potash occurs in the Neubauer procedure, and without a measurement of the residual exchangeable content, agreement between the initial exchange value and the Neubauer value may not correctly indicate the absence of release.

The ability of a plant to utilize nonexchangeable potassium would be expected to depend on such characteristics as rate of growth, root habit, and potassium requirements. Drake and Scarseth (1940) grew 13 crop plants in pots on a 2:1 mixture of Crosby silt loam and sand at various levels of added potash. The extent of response to potash applications was inversely proportional to the plant's ability to absorb native soil potassium. Timothy utilized potassium that was not available to most of the crops; carrots, buckwheat, wheat, and Sudan grass also absorbed potassium in excess of the exchangeable value. Evans and Attoe (1948) compared the utilization of nonexchangeable potassium of six soils by oats and ladino clover. The clover extracted more from the four soils of relatively high exchange level, but oats removed more from the two soils of low exchange level, the difference being attributed to the ability of oats to grow well at low levels of available potassium.

When the exchangeable potassium is below the equilibrium level, release from nonexchangeable forms may occur in the absence of plants or of artificial extracting agents. Increases in the exchangeable potassium value of field soils in the spring over that in the autumn, following harvest, are usually ascribed to this process (DeTurk, Wood, and Bray, 1943). The contributory role of concurrent effects, such as drying, freezing, and thawing, and liberation from residues during this period has not been elucidated. Bartholomew and Janssen (1931) observed release to occur during moist storage of soils in the laboratory. Bray and DeTurk (1939) found that storage of moist field soil samples which were at or near the equilibrium level released no further potassium. But the exchangeable potassium contents of soils which had been freed of exchangeable bases by leaching with 0.1 *N* HCl were restored to their initial levels after six months of storage. At that date they considered that the level of exchangeable potassium is important mainly as an index of the ability of the soil to maintain it. Their observations of the tendency of exchange values below and above the equilibrium level to approach this level by the opposing processes of release and fixation formed a basis for their theory of potassium equilibria. Moist storage of Hawaiian soils for 42 months did not change the exchange potassium contents (Ayres, 1949). A partial depletion of the exchangeable cations was followed by a release of small amounts of potassium. Complete removal resulted in a further increase, the less weathered soils showing the greater release. On the average, Ca-saturated soils liberated 2.5 times as much potassium as did H-saturated soils, but liming did not release potassium if the exchangeable potassium was not removed first. The average release during cropping was about eight times as great as from the same soils stored moist while H-saturated.

It has been known for some time that drying at ordinary and elevated temperatures increases the fixation of potassium by many soils when the exchange level is relatively high. In 1939 Bray and DeTurk reported that heating soils at 200°C. could also release potassium, when the initial exchange level was low. They attributed this result to the effect of heat in hastening a return to the equilibrium potassium level. Campanile (1950) determined the exchangeable potassium of a group of cultivated soil samples before and after heating for 20-25 days at 30-40 and 50-60°C., respectively; the lower temperature approximately doubled or tripled the exchange potassium of some soils, and the higher temperature raised some values even higher. A similar process at high field soil temperatures would be of importance. Oven-drying at 70°C. of some Indiana soils increased the exchangeable potassium over that in the moist state, in several cases doubling it (Rouse and Bertramson, 1950).

Of four soils studied by Walsh and Cullinan (1945), the three of lower exchangeable K content released nonexchangeable K in cycles of wetting and drying at 45°C. One soil was subjected to 0, 1, 3, and 5 such cycles, and each of the four treatments was followed by growth of two crops of mustard; the respective uptakes of K were 45, 61, 104, and 176 mg. of $K_2O$, and the increases over the control were attributed to the release of K. Ayres (1944) interrupted the leaching of three Hawaiian soils in order to sample the columns for exchangeable K. The air-drying preliminary to the analysis resulted in a subsequent temporary increase in the rate of leaching of K from the soils. This effect evidently can be assigned to a release of nonexchangeable K by the air-drying operation. Seatz and Winters (1944) presented data which suggest the release of nonexchangeable K by air-drying at ordinary temperatures.

In a study of ten samples of cropped Wisconsin soils, Attoe (1947, 1949) found that air-drying increased the exchangeable potassium content over that in the moist state except for the sample of highest exchange level. The percentage increases were 4, 4, 12, 33, 34, 35, 49, 58, and 90, the highest being that for the Miami soil. When this soil was dried at relative humidities ranging from 10 per cent to 100 per cent, the release increased with decreasing humidity. Seven plantings of oats were grown on Miami and Spencer silt loams in two series. After each harvest, the soil of one series was air-dried, that of the other kept moist. The Miami soil released a substantial amount of potassium at each air-drying, which increased the total potassium uptake from 508 to 824 lb. per acre. The Spencer soil released only about 10 lb. at each drying, and this resulted in an increase in uptake of 193 to 230 lb. per acre. On the basis of results obtained on Wisconsin and Ohio soils, Evans and Simon (1950) proposed for the assessment of the potassium-supplying power of soils a method involving a succession of cycles of alternate extractions with 0.5 *N* HCl and dryings at 80°C. This combination of the release agencies of acidity and drying exhibited a high degree of correlation with potassium uptake by oats and alfalfa.

It was reported that after intensive cropping at the minimum exchange potassium level, several soils released potassium upon air-drying and more upon drying at 105°C.—a sample of Sable silty clay loam increasing from 100 to 250 lb. of exchangeable $K_2O$ per acre upon air-drying (Reitemeier *et al.*, 1948). It has been subsequently established that this release mechanism in these soils is primarily a property of the clay-size fraction. Lee (1948) found the exchangeable K of prairie soils of Illinois to increase markedly upon air-drying but not to increase further by oven-drying. Larson and Allaway (1950) removed the exchangeable bases from a large number of Iowa soils by acetic acid treatment; the H-saturated soils were air-dried and then stored moist for 360 days. On the average, of the release due to both the air-drying and moist storage, 48 per cent was attributable to the air-drying operation. Larson (1949) suggested that the release from these soils on drying was the result of a shift within the release-fixation mechanism, while that during moist storage was due to weathering of primary minerals.

Probably the most commonly used rapid method for the estimation of the reserve supplying power of soils is that of extraction by strong acids, either with or without the prior removal of exchangeable cations.

Fraps (1927) called the acid-soluble potassium of soils that extractable by HCl of specific gravity 1.115 at 100°C. for ten hours (previously used by Moore), and later (1929) that extracted by 12 per cent HCl during one day at room temperature. Wood and DeTurk (1941) boiled 10 grams of soil freed of exchangeable potassium with 100 ml. of 1 *N* $HNO_3$ for ten minutes. They utilized the value of acid-soluble potassium thus obtained as an index of the more readily available nonexchangeable potassium. This same procedure was used by Rouse and Bertramson (1950) and also by Reitemeier *et al.* (1948), except that in the latter case, exchangeable potassium was not removed before acid treatment but was subtracted from the total acid-extractable value. Between the acid-soluble value and the release by prolonged ladino clover cropping, the former found correlation and regression coefficients of 0.96 and 0.92, while the latter observed values of 0.94 and 0.78, respectively. On an equal weight basis Rouse and Bertramson (1950) found the acid-soluble potassium concentrated in the $< 1\text{-}\mu$ fraction, but because of the high proportion of the soil in the coarser range, about one-half of the supply was in the 5–53 $\mu$ range. Ayres (1949) extracted exchange-free soils with 1 *N* HCl at 95°C., and the potassium values were related to the release values by cropping and moist storage. Attoe and Truog (1946) defined moderately available potassium as that extracted by 0.5 *N* HCl in two hours of shaking above that removed by $NH_4$ acetate. Corn and oats were grown on Spencer silt loam which had been leached with (*a*) water, (*b*) 0.8 N $CaCl_2$-0.2 N $MgCl_2$, and (*c*) 1 N HCl followed by the Ca-Mg solution. A smaller yield was given by (*b*) than by (*a*), but (*c*) reduced it to a very low value.

Electrodialysis had been previously investigated as a method of extracting available quantities of nutrients, especially phosphorus and potassium. Several of the investigations had indicated the extraction, during one or several days, of quantities of potassium in slight excess of the exchangeable amount. Since the goal of these studies with respect to potassium was the extraction of a quantity equivalent to the exchangeable fraction, the relationships of this excess were not examined at the time. Recently, Ayres (1949), Ayres, Takahashi, and Kanehiro (1947), and Reitemeier *et al.* (1948) used electrodialysis for periods of 30 days or more as a method for the extraction of nonexchangeable potassium. By 1-4 days a quantity equivalent to the exchangeable fraction has been removed, followed usually by a period of continuously decreasing rate and then a virtually constant rate of release for a substantial period of time, often until the completion of the dialysis run. The total release during a 30-day period was found by Ayres (1949) to be related to the release by H-saturated soils during moist storage and by Reitemeier *et al.* (1948) to show a high degree of correlation with release by ladino clover cropping and other extraction methods. Where increasing amounts of applied potassium had been fixed in Caribou loam, the extent of the fixed form was indicated primarily by the quantity released in the region of continuously decreasing rate, which suggests that the fixed potassium was more readily available than the bulk of the native potassium of the soil. This agrees with the cropping results on this soil.

Acid extractions and electrodialysis are similar methods in that the soil is H-saturated during both procedures. Appreciable decomposition of minerals as a consequence of the acidity is usually visible, and it is presumed that much of the potassium is liberated as a result of crystal structure breakdown. Since the prevailing notion of release by natural processes as cropping and moist storage is that of a slow exchange of water and cations for potassium held between silicate layers, the high correlations which have been observed between acid methods and the more natural methods are somewhat difficult to explain on the basis of release mechanism. The correlation between cropping and acid methods does appear to be much poorer for soils of low supplying power, because strong acids extract appreciable nonexchangeable quantities from soils which yield only negligible amounts to plants.

Peech (see Merwin, 1950) found that by a certain sequence of salt treatments, soils can be made to release substantial amounts of potassium "immediately." The order of extraction was (*a*) $NH_4$ acetate, (*b*) acetic acid or some acetate, (*c*) 80 per cent ethanol, and (*d*) $NH_4$ acetate. The released potassium is that extracted by the second $NH_4$ acetate leaching. By employing the acetates of a number of cations, the release values in pounds of K per acre for Dunkirk soil were as follows: Mg-75, Ca-45, Na-13, Ba-12, H-6, and $NH_4$-4; for Honeoye soil, the corresponding values were: 92, 64, 53, 34, 32, and 4. For both soils. substantial "immediate" release was obtained by saturation with Mg and Ca; saturation with ammonium tended to block the release of potassium, which is consistent with present knowledge of the similarity between the two ions.

In studies on a sample of Ramona loam, Jenny and Williams (Jenny, 1951) found that whereas prolonged leaching with $NH_4$ acetate, 0.1 *N* NaCl, dilute acids, or $H_2CO_3$ removed only negligible or small amounts of nonexchangeable potassium, a Neubauer procedure, and contact with $NH_4$-saturated and Na-saturated Ion-X (Dowex 50) cation-exchange resin released 188, 68–114, and 110–152 p. p. m., respectively. It was stated that H-saturated resin was even more effective than the base-saturated resin. These results were interpreted as evidence (*a*) for the high effectiveness of cation swarms in the replacement of exchangeable potassium by contact exchange and (*b*) against the importance in the supply of potassium to plants of the exchangeable ←→ soluble section of the generally accepted nonexchangeable ←→ exchangeable ←→ soluble equilibrium theory.

It has been shown that within the development series of Illinois soils formed from Peorian loess on Illinoian till, soils at earlier stages of development have higher K supplying capacities than those of later stages (Wood and DeTurk, 1941, 1943; DeTurk, Wood, and Bray, 1943). Thus, Sable soil at stage 1 releases more K than Herrick of stage 3, which in turn surpasses Cisne of stage 5. This superiority of Sable over Herrick has been confirmed by a variety of methods including prolonged ladino clover cropping and a Neubauer procedure (Reitemeier *et al.*, 1948). Relatively unweathered soils of the Great Plains region have both high exchangeable K levels and high potassium supplying capacities of nonexchangeable K (Reitemeier, Holmes, and Brown, 1950); intensive cropping for a number of years has reduced the exchangeable K content but not the reserve supplying power.

### 4. *Clay Mineral Forms*

The layer lattice aluminosilicate clay minerals are divided into two categories on the basis of their silica : alumina ratio. One category, called the 1 : 1 type, includes those in which a single silica layer whose silicon ions are surrounded by four oxygen ions in tetrahedral coordination alternates with a single alumina layer having aluminum ions surrounded by six oxygen or hydroxyl ions in octahedral coordination. Examples of this type are kaolinite, halloysite, nacrite, and dickite. Expansion of the interlayer distance of these minerals by hydration does not occur and exchangeable cations are bound only by unsaturated bonds on the edges of the crystal particles. These cations are readily replaceable by other cations in the usual sense. Potassium is not fixed or retained in a form requiring special treatment or length of time for release (G. W. Volk, 1938; Hoover, 1945; Mortland and Gieseking, 1951). Consequently, these minerals play a simple role in the potassium relationships of soils.

The other category, known as the 2 : 1 type, includes a variety of minerals having a unit structure containing four layers of oxygen and hydroxyl ions, two layers of silicon ions, and one layer of aluminum ions. Each of the silicon layers lies between two of the oxygen-hydroxyl layers. The aluminum layer lies between the two middle oxygen-hydroxyl sheets, and the oxygen and hydroxyl ions of these two layers are shared in octahedral coordination by the aluminum ions and in tetrahedral coordination by the silicon ions. Actually, the composition indicated is that of pyrophyllite, which is not considered a clay mineral, and which, like kaolinite, binds exchangeable cations only on the edges of the particles. When the two aluminum ions of the unit cell are completely substituted by three magnesium ions, the unit remains electrically neutral as in pyrophyllite and the mineral is called talc. This replacement within the octahedral aluminum layer is a form of isomorphous substitution and is often termed "proxying." Similar substitution occurs for Si within the tetrahedral layers. Incomplete octahedral or tetrahedral replacement by cations of lower valence is accompanied by a resultant negative charge on the lattice. Common substitutions are $Mg^{++}$ and $Fe^{++}$ for $Al^{+++}$, and $Fe^{+++}$ and $Al^{+++}$ for $Si^{++++}$. The negative lattice charges are compensated by those of cations located between the three-layer units, e.g., $Ca^{++}$, $Mg^{++}$, $K^{+}$, $Na^{+}$, and $H^{+}$.

These interlayer cations are actively or potentially exchangeable by other cations, depending on whether the interlayer distance is sufficient for the ions concerned to pass between the structural units. The ideal composition of muscovite mica differs from that of pyrophyllite in that an Al ion has replaced one of every four Si ions of the tetrahedral layer and the resultant charge is balanced by one K ion located between the lattice units. In addition to this proxying of Al for Si, biotite micas have substantial substitution of Mg and Fe for octahedral Al. In ideal phlogopite, the high-Mg biotite, the Al has been completely replaced by Mg. Muscovite contains 350 me. of nonexchangeable (potentially, not actively exchangeable) potassium per 100 grams (Jackson *et al.*, 1948). Not only is this a relatively high value, due to the great extent of substitution, but because of its proximity to the site of the tetrahedral negative charges the K is more strongly bound than it would be by an equal number of octahedral charges. The lattice of the unaltered micas is nonexpanding with a c-axis interplanar spacing of 10 Å, and cation exchange can occur only at the edges and exterior faces of the particle.

The 2 : 1 type clay minerals possess a variety of ion proxying which, to a great extent, determines such mineral properties as expansibility along the c-axis, cation exchange capacity, and K fixation. Those which have been identified as occurring in soils to greater or lesser extents include: (*a*) the montmorillonitic series, comprising montmorillonite and beidellite species; (*b*) the illite group (hydrous micas), which includes the clay mica initially called illite (Grim, Bray, and Bradley, 1937) having a basal spacing of 10 Å, and others of variable $K_2O$ and $H_2O$ content and basal spacing; (*c*) vermiculites, recently shown to be essentially biotite with Mg replacing the interlayer K; (*d*) chlorites; and (*e*) interstratified minerals in which layers of two or more of the preceding types occur in a more or less random alternation within the same particle. The negative lattice charges, which occur in all these minerals, vary in quantity and strength depending on the extent and site of the lattice substitutions. Interlayer cations include $Ca^{++}$, $Mg^{++}$, $K^{+}$, $Na^{+}$, and $H^{+}$. In addition to ion proxying, three-layer aluminosilicates differ with regard to the regularity of stacking and orientation of the layers, randomness in this respect being especially pronounced in the clay minerals. The montmorillonite usually considered typical has a partial substitution of Mg for Al as the predominant proxying; in beidellite the characteristic partial substitution is Al for Si. This series is characterized by great expansibility of the lattice and high exchange capacity. Vermiculite can expand from 10 to 14 Å and its exchange capacity is about 50 per cent higher than that of montmorillonite (Barshad, 1948). The other minerals usually exhibit little or no lattice expansion, and cation exchange occurs mainly on particle edges and exterior faces. Of the different minerals in their natural states, only hydrous micas have potash contents of several per cent or more; illite samples from mineral deposits usually contain about 5-7 per cent $K_2O$, which is about one-half of that of many unaltered micas. Hydrous micas are broadly defined as mica-like clay minerals having appreciably lower $K_2O$ and higher water contents than ordinary micas and little or no lattice expansibility. It will be shown that other minerals, e.g., montmorillonite, may have appreciable potassium contents as a result of fixation reactions.

The description and discussion of relationships of the aluminosilicate minerals necessarily have been brief and incomplete. For a more detailed understanding of the micas and clay minerals, one or several comprehensive reviews should be consulted (*General:* Gieseking, 1949; Grim, 1942; Hendricks, 1942; Jackson, Pennington, and Mackie, 1949; Marshall, 1949; Nagelschmidt, 1944; *Montmorillonites:* Ross and Hendricks, 1943; *Micas:* Hendricks and Jefferson, 1939; Pauling, 1930).

*a. Original Potassium Content.* The $K_2O$ contents of the fine colloid fractions of Maquoketa shale and Pennsylvanian underclay, which Grim, Bray, and Bradley (1937) described as their purest separated materials were 6.93 and 6.09 per cent, respectively; Goose Lake clay, having an average $K_2O$ content of 5.75 per cent and a higher water content than other illites (Grim and Bradley, 1939), was later found to have a maximum basal spacing of 12-13 Å when Ca-saturated (Jackson and Hellman, 1942). Jackson *et al.* (1948) suggested the occurrence of hydrous mica intermediates between the illite and montmorillonite weathering stages. Barshad (1950) considered that the mineral of expanded lattice which has been reported to be associated with hydrous mica is not necessarily montmorillonite but perhaps an altered mica in which the K has been replaced by H, Ca, and Mg ions.

Maegdefrau and Hofmann (1937) concluded that from the viewpoint of structure, hydrous micas resembled muscovite rather than biotite. They have been grouped together with muscovite in the heptaphyllite micas in the ideal type of which only two-thirds of the octahedral cation positions are filled (i.e., Al predominates, not Mg) (Grim, 1942; Hendricks, 1942). It will be recalled that Walker (1949) observed biotite to weather to vermiculite, not toward illite. Caillere and Henin (1950) stated that treatment of muscovite with $H_2SO_4$ tended to form illite.

The distribution of hydrous mica within the clay-size fraction is not uniform (Pennington and Jackson, 1948). Whereas the proportion of montmorillonite tends to increase with decreasing particle size, illite is not abundant in the finest fractions. Jackson and Hellman (1942) reported that no fine clay from any soil had been found to consist principally of hydrous mica. Only in geological deposits did the finest fractions show absence of montmorillonite. Bray (1937) postulated a weathering mechanism of 0.1–1 $\mu$ mica particles in which the ends weather first, by hydration and replacement of K, to thin sheets of beidellite which slough off by physical weathering to become the superfine clay of the soil. The clay fractions of three Illinois soils showed a tendency to become lower in K content with increasing age. Wood and DeTurk (1943) suggested that in the older soils, K of illite had been removed to a greater distance within the particles, thus accounting for the lower total K content. By the addition of sodium cobaltinitrite to illite, White (1951) was able to extract about one-tenth of the total K and thus effect a partial conversion of illite to an expanding lattice structure as indicated by x-ray patterns.

Rouse and Bertramson (1950) made x-ray diffraction spectrograms of the $< 0.2$, 0.2-1, 1-5, 5-20, and 20-53 $\mu$ fractions of a number of soils. For the two smallest sizes they obtained significant correlations between the area under the illite peak of the spectrogram and the potassium supplying power of the soil by $HNO_3$ extraction; for the 0.2-1 $\mu$ fraction $r$ was 0.84, and 0.82 for the $< 0.2$-$\mu$ fraction.

Although hydrous micas are important in soil potassium relationships, their identification and estimation, and knowledge of their behavior in soils remain unsatisfactory. This results from a variety of causes such as diffuse x-ray diffraction spectra, the existence of differences in basal spacing (Jackson and Hellman, 1942), and in $K_2O$ and $H_2O$ contents (Grim, Bray, and Bradley, 1937; Grim and Bradley, 1939), dissimilarity of those of soils and of geological deposits, possibly general occurrence in mixed layer minerals (Hendricks and Dyal, 1950), confusion with small particles of unaltered and degraded micas, and inadequate knowledge as to mode of formation (Jackson *et al.*, 1948). Variables such as these complicate the estimation of the relative importance of hydrous micas in the release of potassium by soils. On the basis of information extant it can be generalized that the proportional contribution compared to that by silt and sand fractions varies with different soils. Illinois workers (Bray, 1937; Wood and DeTurk, 1943) have stressed the importance of the clay fractions. Conversely, Missouri workers (Albrecht, 1943; Graham, 1943) have concentrated their attention on silt and sand fractions. It is quite possible that for their respective soils, the emphasis was correctly placed. Recent work by Reitemeier, Brown, and Holmes * supports the idea that soils of substantial hydrous mica content vary markedly in this respect.

*b. Difficultly Exchangeable Potassium by Fixation.* In a study of the Hoos field at Rothamsted, Dyer (1894) calculated that of 4,084 lb. of $K_2O$ per acre applied over 38 years, approximately one-half was accounted for by that removed in crops and that extractable by 1 per cent citric acid. Comparison with the adjacent control plot indicated that the other half had become difficultly available. Frear and Erb (1918) examined the potassium status of a plot of Hagerstown silt loam which had received 1,800 lb. of $K_2O$ per acre during a 36-year period. Crop removal and the status of the control plot accounted for one-fourth of this; half of the remainder was extractable by 0.3 $N$ $NH_4Cl$, and the rest had been converted to difficultly soluble forms. Since then it has been established that a high proportion of soils possess the property of fixing applied potassium in difficultly available forms.

Because the definition of available potassium is so dependent on vegetation and time factors, it is more precise to define fixed potassium as applied potassium which is not immediately replaceable by the usual cation exchange reagents as $NH_4$ acetate. This also brings the phenomenon of fixation into a more consistent relationship to the release of nonexchangeable potassium, both native and fixed.

Bartholomew and Janssen (1931) and Hoagland and Martin (1933) claimed that in some experiments the fixation of potash increased during periods of cropping. In the first detailed study of fixation by soils, N. J. Volk (1934) observed relatively little fixation when soils were kept moist compared to that by drying at 70°C.; for Miami and Hagerstown soils, one drying cycle effected 75 per cent of the total fixation induced by 32 cycles. The clay-size fraction was the only one of importance in fixation. The 0.3-2 $\mu$ fraction of specific gravity $> 2.667$ of Hagerstown silt loam from a KCl plot at State College, Pennsylvania, showed strong second order x-ray diffraction lines of "muscovite," whereas that from a control plot showed faint and incomplete lines. The conclusion that muscovite had been formed by K fixation is not justified, because muscovite is a hydrothermal mineral, unlikely to be formed under soil conditions (Kelley, 1948). However, it is quite possible that partial conversion into or restoration of hydrous mica lattices had occurred.

Acid treatment reduced fixation, while $Na_2CO_3$ and $Ca(OH)_2$ additions increased its extent. It was postulated that under alkaline conditions, the fixation process is a combination of K with dissolved $Al_2O_3$ and $SiO_2$ to form an insoluble aluminosilicate. G. W. Volk (1938) observed the same influences of acidity and alkalinity, which he associated with the amount of free alumina; addition of $Al_2O_3$ together with HCl tended to eliminate the reduction of fixation capacity due to HCl alone. On the basis of increased content of dissolved silica at higher pH values, York (1949) also postulated the formation of temporary aluminosilicates in which K is fixed. Mortland and Gieseking (1951) obtained extremely high fixation of K by montmorillonites and illites from potassium silicate. They were unable to conclude whether this occurred by synthesis of mica-like minerals or by a more effective entry of K ions into K-deficient mica lattices.

Chaminade (1936) concluded that the maintenance of exchangeable K saturation at values greater than 4 per cent of the exchange capacity resulted in the maximum possible fixation for the soils he studied. The velocity of fixation increased at higher temperatures, higher pH values, and lower moisture content. A fraction of purposely fixed K was available to Neubauer seedlings, but Chaminade considered fixed K as virtually unavailable to plants. Chaminade and Drouineau (1936) stated that K, $NH_4$, and Mg can be fixed, but that Ca and Na cannot. They envisioned the fixation of cations as a movement into the crystal nuclei of soil colloids. Vazhenin (1936) found the presence of NaCl (and $MgCl_2$) to increase K fixation; he pictured the effect as a prior entry of the lattices of clay colloids by Na, which was subsequently replaced by K.

DeTurk, Wood, and Bray (1943) observed K fixation in soils both under moist storage at ordinary temperatures and by drying at 200°C. provided the initial value of exchangeable K exceeded the equilibrium level. Because of greater amounts of fixed K at increasing K additions and a gradient in the ease of removal, it was suggested that the first K ions fixed occupy positions near the surfaces or edges of particles and penetrate farther between lattice layers with increasing time and exterior K concentration. Added as $K_2HPO_4$, more K was fixed than as KCl, which was explained by an increase in negative charges resulting from replacement of $OH^-$ by $PO_4^{\overline{\overline{}}}$; the cation exchange capacity of Tama soil was increased several milliequivalents by $K_2HPO_4$ treatment. The release of fixed K from H-saturated soils during moist storage increased with the extent of fixation. Fixation of K should not be considered wholly wasteful, because fixed K tends to become available after a period of time when the exchangeable K level has been reduced, and fixation retards loss by leaching; this was also concluded by Blume and Purvis (1939) and by Walker and Sturgis (1940).

The availability to plants of fixed K has been studied by a number of workers. Kolodny and Robbins (1940) grew tomatoes on Wyoming bentonite in which K had been fixed by cycles of wetting and drying at 100°C. They concluded that this form of K, the sole source, was only very slightly available. However, Fine (1941) criticized this conclusion as invalid for these reasons: (*a*) the tomato plant is a poor feeder on K; (*b*) the bentonite was Ca-saturated, so that the Ca : Mg ratio was unfavorable; and (*c*) the availability was compared to that of exchangeable K of eight times the quantity in the fixed form. Fine's experiments indicated that all of bentonite-fixed K was available to corn and wheat, and one-fourth of it to tobacco. Walsh and Cullinan (1945) found that the fixation of K in some soils by wetting and drying cycles caused severe K deficiency and reduced yield of the first subsequent mustard crop. The ultimate effect, however, was release of fixed K. This reversion of fixed to available forms is slow and dependent upon a prolonged moist condition.

Reitemeier *et al.* (1948) compared a group of samples of Caribou loam in which varying amounts of K had been fixed in a long-time field experiment from fertilizer and organic matter additions. The release of fixed K to ladino clover, Neubauer seedlings, and other extractants increased progressively with increasing quantities of applied K. Evans and Attoe (1948) added KCl to soils, heated them at 80°C. for 14 days, leached with $CaCl_2$-$MgCl_2$ solution and grew four crops of oats. On correcting the total K uptake for delivery from exchangeable and native nonexchangeable sources, they determined that 24-47 per cent of the fixed K had been utilized by the oat plants. York (1949) grew alfalfa on Mardin silt loam at different lime levels and with K additions of 100 and 400 lb. per acre. Liming fixed some of the added K with respect to extraction by $NH_4$ acetate of pH 7, but this fixed K was available for five cuttings over a six-month period. Similarly, K fixed by liming during eight weeks of moist storage was completely extractable by $NH_4$ acetate of pH 4.8. Attoe (1947) concluded that there are two types of fixed K: (*a*) in moist soil enhanced by liming and fairly soluble in 0.5 *N* HCl; (*b*) by drying independent of pH and resistant to 0.5 *N* HCl extraction.

The earlier studies on K fixation had not indicated an intimate connection between that phenomenon and the exchangeable cations and cation exchange capacity of a soil or clay. It has been definitely established, subsequently, that K is fixed in positions which normally contribute to the exchange capacity and that the fixation results in a reduction of its magnitude, at least temporarily.

By alternate wetting and high-temperature drying, Truog and Jones (1938) fixed 15-49 me. of K per 100 grams of bentonite which had an initial cation exchange capacity of 124 me. per 100 grams. Miami, Carrington, and Richfield soils fixed 1.5-5 me. per 100 grams. The amounts of K fixed were equal to the reductions in exchange capacity. This is direct evidence that upon drying K is trapped in interlayer exchange positions between some layers of expanding lattice minerals.

Joffe and Levine (1940) found K fixation in $B_2$ horizon samples of Chester, Gloucester, and Montalto soils to be accompanied by decreases in exchange capacity, but the two values were not equivalent except approximately in the Montalto soil. However, the values for the other two soils were so low that they must have been subject to large percentile errors. Graphical relationships for H-saturated Montalto clay and bentonite for fixed K vs. applied K and for exchangeable K vs. applied K were closely similar (Levine and Joffe, 1947). Larger proportions of applied K were fixed at lower K additions; near the addition of an amount of K equivalent to the exchange capacity, the proportion of fixation decreased abruptly. Bailey (1942) observed equivalence between the quantity of fixed K and the reduction in exchange capacity for Wyoming bentonite, a Mississippi montmorillonite, Putnam $B_1$ and Miami $B_1$ horizons. Reduction in exchange capacity of Vina and Ramona soils, due to fixation, was far below the amount of fixed K, but for the clay-size fraction separated from the two soils and for two bentonites, the two values agreed closely (Martin, Overstreet, and Hoagland, 1946). Nevertheless, the amount of K fixed by the whole soil was closely equivalent to the sum of the exchangeable bases (Ca, Mg, Na) which were replaced in the fixation reaction.

In 1940 Hendricks, Nelson, and Alexander reported hydration studies on bentonites which indicated that some exchangeable cations are located between silica layers. By controlled vapor hydration, the maximum basal spacing exhibited by K-saturated bentonite was 12 Å, whereas a value of 16 Å was obtained for bentonite saturated with other common cations. It was concluded that K ions are not hydrated under this condition. Bailey (1942) increased the basal spacing of K-fixed bentonites from 12.6 to 16 Å by subsequent saturation with Ca. After being dried at 110°C., K-saturated montmorillonite showed a basal spacing of 10 Å (Jackson and Hellman, 1942). Recently, Hendricks and Dyal (1950) observed that K-saturated montmorillonites and nontronite retained only 40-70 per cent as much ethylene glycol as did the corresponding H, Ca, and Na materials; the fixation accompanying K-saturation contracts the lattice and thus renders some internal surfaces unavailable to glycol molecules. Page and Baver (1940) related the fixation of cations by bentonite and Miami clay upon drying at 100°C. to the size of the unhydrated ions. Not only K, but $NH_4$, Rb, Cs, and Ba could be fixed; it was postulated that the sizes of these ions were close to that of certain free spaces within the lattice, e.g., the crystal lattice diameter of K is 2.66 Å, that of oxygen (and the hexagonal oxygen cavity) 2.80 Å.

Wear and White (1951) considered the reduction in exchange capacity of clays upon fixation at 105°C. as a measure of the extent of cation fixation. On this basis, Wyoming bentonite fixed 18, 10, and 4 me. of K, Rb, and Na per 100 grams, respectively. They observed no evidence of fixation of Li, $NH_4$, Cs, Mg, Ca, Ba, and Sr. As K-saturated montmorillonite is dried upon heating the lattice becomes so contracted that the interlayer K ions must be located in cavities formed by the superimposition of two voids within hexagonal nets of oxygen ions, one from each silica layer. However, a cation in this position would actually possess 14-fold coordination, not 12-fold, and from ion sizes it was calculated that K forms the most stable, Rb and Na less stable, and Cs and Li unstable configurations. With regard to $NH_4$ and Ba, Barshad (1948) concluded that in dried vermiculite these ions are accompanied by one and two water molecules, respectively. The hydrated ions are larger than the cavity and would effect an unstable configuration.

On the basis of several lines of evidence, Bailey (1942) considered the tetrahedral layer charges resulting from isomorphous substitutions as the important factor in fixation, rather than octahedral charges. Wear and White (1951) arrived at the same conclusion by establishing a direct relationship between the total quantity of K in the crystal structure after fixation and the amount of tetrahedral substitution. The beidellite and illite clays have relatively more tetrahedral charges than the Mg-montmorillonites. They proposed a mechanism of fixation within a mineral of expanding lattice, in which after rehydration some of the layers remain contracted while the remainder re-expand. The relatively great resistance of contracted K-saturated 2:1 type lattices against re-expansion and K replacement results from a combination of two factors, (a) the agreement between the diameter of the K-ion and that of the 14-fold coordination cavity, and (b) the lack of hydration of K ions and the interlayer surfaces when K-saturated.

Stanford (1948) investigated the fixation of K by Wyoming bentonite and illite under moist conditions and when dried at 100°C. Absence of moist fixation over the pH range 4-10 was observed for bentonite; for illite, there was a slight constant rise in fixation with increasing pH, the order of magnitude of fixation being about 1 me. per 100 grams. By drying, bentonite fixed about 5 me. at pH 4 and 2 me. at pH 7-10; illite, instead, fixed about 1 me. at pH 4 and 4 me. at pH 10. The effect of NaOH, $Ca(OH)_2$, phosphate and fluoride in increasing moist fixation by illite was attributed to removal of H, Fe, and Al ions in the interlayer positions, which replace K when illite is kept acid; under alkaline conditions, K is replaced by Ca, Mg, and Na. The decrease in fixation by bentonite with increasing pH might be due to (*a*) competition between K and Na; (*b*) swelling in the alkaline range; or (*c*) precipitation of Fe and Al between silica sheets blocking internal exchange positions. Wiklander (1950) obtained greater K fixation by an illitic soil clay after it had been treated with Ca or Na than with H, K, or $NH_4$, of the order of 10-20 times. Extent of fixation increased somewhat with increasing pH, an effect attributed to H and Al saturation at higher acidities. The increased fixation obtained by liming was thought due to both the increase in pH and replacement of exchangeable Ca by K. A comparatively slight exchange of $K^{42}$ with fixed K of this clay, about 5 per cent of that considered possible, indicated that the transfer of fixed K to exchangeable form was very low despite high temperatures and long reaction periods.

Jackson and Hellman (1942) found that 0.7-0.9 per cent of $K_2O$ could be fixed in nonexchangeable form in montmorillonite of bentonite and soil clays without affecting the position of the 001 x-ray line, provided the complete dispersion and preparation procedure was given the clay following the fixation treatment. Buehrer, Robinson, and Deming (1949) subjected two Ca-saturated bentonites and the clay fractions of 11 Arizona soils high in montmorillonite to four wetting and drying cycles while in contact with KCl. In all but one case the K content of the clay was increased, expressed as per cent $K_2O$; the majority of the clays underwent a concurrent decrease in cation exchange capacity. They observed that clays which normally puddle easily, forming hard clods, became friable after the KCl treatment and upon rewetting did not swell to as great an extent as before. After boiling montmorillonite in 1 *N* KOH solution and drying, Caillere and Henin (1950) noted the appearance of a 10-Å spacing line, which they attributed to a conversion to illite. By the same treatment they changed the basal spacing of vermiculite from 14 to 10 Å.

The existence of vermiculite, or vermiculite-like minerals, in soils has been claimed in recent years. Barshad (1946) found Sweeney soil clay to contain hydrobiotite, which is an interstratified mineral composed of alternating layers of vermiculite and hydrous mica. Vermiculite has been reported to occur in soils of North Carolina and Scotland (Coleman, Jackson, and Mehlich, 1950; Walker, 1949). Several studies which have been made on the cation relationships and hydration of vermiculite are therefore of interest in a discussion of soil potassium (Barshad, 1948, 1950; Walker and Milne, 1950). The cation exchange capacity averages about 150 me. per 100 grams, about 50 per cent higher than that of montmorillonites. This mineral can fix K in a moist state against rapid replacement by $NH_4$, as cations producing contracted lattices are fixed against others producing contracted lattices. Basal spacings with K and $NH_4$ as the adsorbed ion were 10.1 and 10.3 Å, respectively, whereas, Li, Na, and Mg provided spacings of 12.2, 14.7, and 14.4 Å, respectively. When immersed in water, vermiculite saturated with Mg, Ca, Ba, H, Li, or Na contains two monomolecular layers of water between structural units, but montmorillonite with the same ions shows four or more layers. Under the same conditions, K, $NH_4$, Rb, and Cs vermiculites show no hydration, but the respective montmorillonites show an expansion equivalent to one water layer.

### 5. *Relationships and Equilibria among the Various Forms*

That the various forms of soil potassium are interrelated has been made evident by the preceding discussion. Frequent reference has been made to the probability of the existence of an equilibrium between some or all the manifestations. The basic concept of such an equilibrium is that a change in magnitude of one of the forms will tend to be compensated by movement from and between all the other forms. However, variations in the ease of replacement of potassium, which exist within each of the forms provide a more or less continuous gradient of K motility and availability throughout the entire soil K system. According to Page and Williams (1925), Hissink should be credited with the first proposal of the idea of an equilibrium among the different forms of potassium. Soils subjected to prolonged intensive cropping were observed by Hoagland and Martin (1933) to reach a minimum limiting value of exchangeable K which thereafter remained constant. In some soils the rate of release of K from nonexchangeable forms during maintenance of this level was adequate for normal plant growth, but in others it was too low, and the plants were deficient in K. This has been confirmed repeatedly by other workers.

Both under conditions of moist storage and of drying at 200°C., Illinois soils would decrease or increase in exchangeable K content depending on whether the initial exchange level was relatively high or low; different soils had characteristic levels which they would tend to approach from either direction (Bray and DeTurk, 1939; DeTurk, Wood, and Bray, 1943). High temperatures were regarded as an agency for hastening the approach to the equilibrium exchange level. Ayres (1949) found no release of nonexchangeable K from field soil samples during moist storage but substantial release when the samples were first freed of exchangeable cations. It has also been observed that either fixation or release may occur upon air-drying, the direction of the K movement being dependent on the initial exchangeable K content (Attoe, 1947). Freezing and thawing cycles appeared to produce similar results (Fine, Bailey, and Truog, 1941).

Because he and Williams were able to extract appreciable quantities of nonexchangeable K within a few days by Neubauer and cation-exchange resins, Jenny (1951) is inclined to question the importance of the equilibrium concept. On the other hand, Peech and Merwin (see Merwin, 1950) claim that soils saturated with certain cations may release K almost immediately, but consider this a rapid manifestation of the equilibrium principle; Ca-soils appeared to reach an equilibrium level quickly, while H-soils required time of the order of weeks. Although Ayres (1949) found exchangeable-freed soils to release K while fallow, the utilization of nonexchangeable K by plants during the same period of time far exceeded this rate. Findings of Reitemeier, Brown, and Holmes * substantiate this increased release by cropping.

Distinctions between exchangeable, fixed, and native nonexchangeable forms of K have been seen not to be sharp but of a nature to be expected in natural bodies. The definition of an ion as nonexchangeable depends somewhat on the method used to replace it. The wide differences in ease with which Barshad (1948) found the interlayer cations of vermiculite to be replaced is an extreme example of this. He was able to form "biotite" and vermiculite reversibly from the same material by the substitution of K and Mg for each other. The "exchangeable" K was much more easily replaced by Mg and Na than by $NH_4$ ions, because both K and $NH_4$ produce contracted lattice structure in the moist condition, while Mg and Na do not. Montmorillonite saturated with K must be dried in order to effect fixation of of interlayer K ions by lattice contraction. Hydrous micas apparently fix K both while moist and upon drying; interstratifications and variable spacings complicate the establishment of the fixation-release mechanism of this group of minerals.

The importance of the characteristic properties of the potassium ion in the operation of the fixation-release-exchange K economy of the soil is well illustrated by the contrast between its behavior and that of sodium. By the fact that K is more highly adsorbed at and less readily replaced from exchange positions, Jenny (1931) explained the relative accumulation of K in the soil exchange complex and of Na in the oceans.

The widening of the exchangeable K : Na ratio is more pronounced the greater the extent of leaching. Thus, podsols and tropical soils have wide K : Na ratios, whereas but little loss of K and Na is indicated for chernozems. Larson (1949) considers the Na economy of soils much simpler than that of K. The release of Na occurs by breakdown of Na-bearing feldspars and not through replacement of interlayer lattice ions. The Na thus released is not subject to fixation as is K, is loosely retained by cation exchange bonds, is usually only slightly absorbed by plants, and is easily displaced downward by leaching. On the other hand, K may be liberated to the immediately exchangeable form both by decomposition of K-bearing feldspars and by replacement of interlayer K ions of micas. A part of this released K may be refixed between the layers of particles of micaceous and montmorillonite minerals. Plants tend not only to increase the release of nonexchangeable K but to maintain exchangeable and soluble forms at low levels. The return of plant residues and roots to the soil will result in the liberation of their K to soluble and exchangeable forms and in a stress in the direction of fixation.

## III. Influence of Other Cations on Forms of Soil Potassium

Since potassium is one of the group of exchangeable cations, it would seem only logical that mutual interrelationships would occur among them. Of the other cations whose effect on the behavior of K has been studied, probably calcium and hydrogen have been most extensively investigated, and recently attention has been devoted to the interrelationships of K and $NH_4$. Because the contents of exchangeable Ca and H in soils normally are complementary in magnitude, the influence of these two ions is considered jointly. The discussion of $NH_4$ is limited to its similarity to K in undergoing fixation and mutual effects resulting therefrom.

### 1. *Calcium and Hydrogen*

Considerable attention by a large number of workers has been concentrated on the effects of these two ions on the behavior and availability of soil K, because of the importance of liming in the management of acid soils. Some experimental results have been briefly mentioned in preceding sections, but the large volume of work on this subject and apparent contradictions arising from it necessitate a more detailed review in a separate section. Liming or increased saturation of acid exchange complexes with calcium has been shown to affect soluble K, exchangeable K, and both release and fixation of nonexchangeable K, but the effects on some soils with respect to certain of these forms of K appear to be negligible. The physiological specificities of the various plants further confuse the delineation of overall K availability. Ehrenberg (1919) attributed decreased K uptake and low yields on limed soils to an "antagonistic" effect of Ca upon K. He formulated what has since been known as "the lime-potash law," which means that when the Ca concentration is relatively high, plants may not be able to absorb their required K at an adequate rate. It is currently realized that in many of the earlier studies, the distinction between (*a*) the effects of Ca, H, and lime on the distribution of soil K among its various forms and (*b*) the physiological response of plants to concentrations and ratios of Ca and K, especially the immediately exchangeable and soluble forms, has not been adequately considered.

*a. Soluble and Exchangeable Forms of Potassium.* For a considerable period after the time of Liebig and his influence (Jenny and Shade, 1934) it was generally accepted that lime liberated K from soils into soluble forms and thereby rendered it available to plants. Doubt was cast on the validity of this idea by experimental results beginning to appear in the early part of this century. Thus, in 1916 Lyon and Bizzell reported that lysimeter studies indicated that lime did not increase the amount of water-soluble K as measured by leaching losses nor did it increase the K content of the crops. Application of 200 lb. of $K_2SO_4$ per acre per year did not increase the quantity of K in the drainage water but did increase that of Ca and Mg. Briggs and Breazeale (1917) were unable to increase the solubility of K in orthoclase and orthoclase-bearing soils by shaking with $Ca(OH)_2$ solutions for a number of days. Gypsum depressed the solubility from orthoclase and a soil and reduced the uptake of K from the soil by wheat seedlings.

MacIntire and co-workers (MacIntire, Shaw, and Sanders, 1927; MacIntire, Shaw, Robinson, and Young, 1943; etc.) have conducted extensive investigations on the effect of lime and Ca salts on the solubility of soil K, especially in lysimeters. They reported that neutral salts of Ca can liberate K to the leachings of an acid soil, but that this does not result from CaO and MgO applications. Aqueous extractions actually indicated decreases in soluble K by liming. Calcitic and dolomitic limestones increased the retention by acid Hartsells and Cumberland soils of the K of KCl, $K_2SO_4$, and $KNO_3$, but not by Calhoun soil, because it was initially alkaline. Mann and Barnes (1940) reported relatively high leaching of K from an acid soil during 50 years of wheat and barley cropping; however, additions of lime, $NaNO_3$, and even $(NH_4)_2SO_4$ when used in small amounts, decreased the quantity of K leached. Mehlich (1943) measured the extent of winter leaching of exchangeable K from plots of Creedmoor sandy loam in which the pH ranged from 4.4 to 7.5; with increasing pH, the percentage loss of exchangeable K by leaching decreased. He concluded that acid subsoils do not retain nutrients despite high clay contents, and should be limed.

Jenny and Shade (1934) disputed such findings of increased retention of K by soils upon liming. Their additions of $Ca(OH)_2$, $CaCO_3$, and a variety of neutral, alkaline, and acid Ca salts to permutite, bentonite, Putnam clay, and soils, invariably transformed some exchangeable K to the soluble form. They considered this result the only one possibly consistent with the principles of cation exchange. Their exchange materials were initially saturated with K except where the H saturation of Putnam clay was regularly varied, and even in that series the final pH ranged only from 7.37 to 7.95. Jenny and Ayers (1939) concluded that the exchangeability of adsorbed K decreases with decreasing degree of K saturation of the exchange complex, but that this effect is influenced by the nature of the complementary ion, e.g., Ca, $NH_4$, Na or H. Intake of K by excised barley roots followed the same principle; they stated that with respect to effect on reducing K intake, Ca was lowest, H and Na intermediate, and $NH_4$ highest. This interpretation of their experimental differences between Ca and H requires qualification on the basis of their own evidence. Their conclusion that neutralizing an acid soil with Ca will make exchangeable K more available has been criticized (Shaw, MacIntire, and Hill, 1949) as being inconsistent with their own theory concerning the effects of complementary cations.

Bray (1942) considered the emphasis placed by Jenny and Ayers on the influence of the degree of K saturation on K availability as too strong, because exchangeability depends on many variables; more K can be replaced from some soils of lower K saturation and exchangeable K content. Liming decreases the relative amount of K replaced by an electrolyte, but Bray stated that cation exchange equations do not include effects of secondary reactions which may reverse the expected trend. Mehlich (1946) considered the differing effects of Ca saturation on K replacement found by Bray and by Jenny and Ayers due to different types of colloid; Bray used an organic-beidellitic-illitic type, Jenny and Ayers a montmorillonitic type.

The lowest degrees of K saturation studied have usually been relatively high, e.g., that of Jenny and Ayers was 10 per cent. Wiklander and Gieseking (1948) discounted the commonly accepted opinion that an exchangeable cation becomes more difficult to replace as its quantity becomes less and favored the principle that whether the replaceability increases or decreases thereby depends upon the nature of the complementary ion. The complementary ion principle can be expressed thusly: Of two cations, which are adsorbed complementary to a third cation, that one which is adsorbed the more tightly will effect the higher exchangeability of the third ion. By using radioactive isotopes $K^{42}$ and $Sr^{90}$ as analytical tools they were able to reduce the degree of saturation to an extremely low range, e.g., the K saturation levels of Amberlite IR-1 resin were: 0.1, 1, 5, 10, 50 and 99.9 per cent. At the highest saturation, the replaceability by $H^+$ was 50 per cent; when Ba was the complementary ion the value rose to about 70 per cent at the lowest K saturation, and when Na was complementary the value decreased to about 40 per cent. The change in liberation over the entire range of saturation was roughly linear, which indicates no abrupt drop in K availability at even extremely low exchangeable K levels. If Ba on the resin may be assumed to act similarly to Ca and H in soils, the availability of soil K would be expected to increase percentage-wise at decreasing K levels; actually, the change within the range of 0.1-5 per cent is too slight to be of any practical importance. Ayres (1941) measured the adsorption of K and $NH_4$ by two Hawaiian soils from percolating salt solutions of concentrations 0.1, 0.01, and 0.001 N at Ca saturations ranging from 0 to 100 per cent. As would be expected, adsorption increased with increase in the concentration. Increasing Ca saturation increased adsorption of both K and $NH_4$ markedly, at all three concentrations; adsorption of K from 0.1 N KCl increased from 3 me. per 100 grams at 0 per cent Ca to 16 at 100 per cent Ca saturation.

Peech and Bradfield (1943) undertook the clarification of the confused situation concerning the effect of lime and Ca on exchangeable and soluble K and the availability of K to plants. The addition of lime may have no effect, may decrease, or may increase the concentration of K in the soil solution depending on the initial degree of base saturation; on the other hand, gypsum or other neutral Ca salts should invariably liberate exchangeable K. Hydrogen ions are more strongly adsorbed than Ca ions; on the basis of the complementary cation principle, therefore, the replacement of H by Ca in liming should increase the exchangeable K at the expense of the soluble K. However, this effect of lime requires the presence of neutral salts of strong acids. In their absence, the soluble K will increase upon liming, because in salt-free systems the clay hydrolyzes, especially at high base saturation; this explains why Jenny and Shade obtained liberation of exchangeable K by $CaCO_3$ addition. Even in the presence of such salts, the addition of excess $CaCO_3$ and the resulting abruptly increased soluble Ca concentration will liberate adsorbed K. In presence of neutral salts, increasing Ca saturation by liming increases the Ca content and decreases the K content of the soil solution; the Ca : K ratio in solution therefore increases, and at high Ca saturation may repress the absorption of K by plants. In the absence of neutral salts, moderate lime applications should increase the K concentration in the soil solution but have only a slight effect on the Ca:K ratio in solution. In this case, the absorption of K should remain unaffected or even be increased by lime additions. The conclusions with respect to availability of K to plants were based on the concept that plants absorb the major part of their nutrient cations from solution. Later, however, McLean and Marshall (1949) interpreted activity measurements of K-H and K-Ca bentonite systems as indicating that Ca is more firmly held by montmorillonite than is H.

Some recent plant experiments involving the lime-potash law indicate that it operates only where the exchangeable K is very low, and thus is not a general principle. Many older experiments were interpreted incorrectly for such reasons as use of per cent K in the plant as a measure of K availability instead of total uptake of K, and neglect of considerations just discussed. The results of a few of the later experiments will be discussed briefly. Hester and Shelton (1936) grew lima beans on three soils limed to various levels, and measured the quantities of K absorbed and that leachable by water. Water-soluble K decreased with increasing Ca saturation up to excess lime, where it increased; where yields were roughly equal, K absorption followed the trend of water-soluble K. Total K uptake increased with increasing pH, and was even higher in presence of excess lime than at the next lower lime level. Addition of lime to Norfolk fine sandy loam did not reduce absorption of K by bean plants, which, instead was primarily a function of the amount of K applied (Carolus, 1938); in some cases Ca increased the K content slightly. Hunter, Toth, and Bear (1943) grew alfalfa on Dutchess shale loam which had initial exchangeable Ca:K ratios of 1 to 32. During growth, some ratios increased to over 100, which was adjudged to be the "critical" ratio with respect to K adequacy. Although an initial ratio of 4:1 was considered the optimum for the period of the experiment, normal growth was obtained at ratios between 1:1 and 100:1. From studies with alfalfa on 20 New Jersey soils, Bear and Toth (1948) concluded that the ratios of cations in alfalfa bear but little relation to those on the exchange complex of the soil. Calcium dominates the soil, but K the plant, which absorbs more K than needed, in luxury consumption, if the soil Ca is not relatively high.

Rogers (1948) reported that although liming reduced the K content of peanut plants by 30 to 46 per cent, total absorption of K increased because of a large response in yield to lime. Earlier (1945) he had observed that either lime or potash applied alone to a soil might be of no value and sometimes actually cause reduced yields, but when the two nutrients were applied in the proper balance highly beneficial results could be achieved. Carolus (1949) found that lime applied to an acid soil was of no benefit to tomatoes when the exchangeable K was low. When lime and potash were added together, highly significant increases in yield were obtained. Van Itallie (1948) investigated the mutual influence of various levels and ratios of exchangeable Ca, Mg, K, and Na on cation absorption by oat plants. The uptake of K was affected only by the rate of K application. Only at very low pH values was absorption increased by addition of Ca as the carbonate; otherwise Ca had no effect on K availability.

Soil experiments obviously confound the effects of the exchangeable-soluble Ca-K relationships and the physiological interactions of the two cations. Sand and water culture investigations involving the effect of levels of these ions have been reported, and four will be mentioned as examples. Collander (1941) observed that in water culture Ca ions did not reduce the absorption of K, whereas Rb greatly depressed it. His conclusion that absorption of a cation is most strongly depressed by very closely allied cations was said by him to differ somewhat from the "current" concepts of ion antagonism. Olsen (1941-43) grew *Sinapis alba, Dianthus barbatus, Hordeum distichum,* and *Tussilago farfarus* in water culture at various Ca and K levels. When the K concentration was 4 me. per liter, the absorption of K on the basis of me. per gram of dry matter decreased with increasing Ca level, but on the total uptake basis some increases of K occurred. At a K level of 0.4 me. per liter *Tussilago* had higher K content, both as per cent and as uptake of K, at increasing Ca concentrations, and the other 3 species had higher total uptake; only at the highest Ca level, 30 me. per liter, were there reductions in yield and uptake. When the Ca level was maintained at 5 me. per liter, 0.4 me. of K per liter was sufficient for optimum growth; the K content of all species increased greatly with increasing K concentration and that of Mg and Ca decreased except for the Ca content of *Tussilago*. It was concluded that when K is present in sufficient concentration there is no harmful effect of high Ca concentration. Corn, beans, and peas were grown in sand containing 0-20 per cent $CaCO_3$ with nutrient solutions having K concentrations of 1.2-30 mg. per liter (Drouineau, Gouny, and Mazoyer, 1950). The K content of the plant after six weeks depended only on the K concentration in solution. The Ca content was reduced by increasing concentration of K in solution, even in presence of a large quantity of $CaCO_3$. Viets (1942) found that Ca and Mg actually furthered the absorption of K by barley in water culture. He suggested that Ca ions can increase the permeability of plant tissues to K ions.

In summation, the more recent evidence definitely refutes the importance of the lime-potash law as a general principle. In addition, even where the exchangeable K content is low, plants may continue to obtain a moderate or adequate supply of K by release from nonexchangeable forms. Actually, the reverse effect, that of K upon Ca, appears to be more important. Although the proportion of exchangeable K to exchangeable Ca and Mg is normally very small, K tends to control the availability of cations to many plants. Its absorption is comparatively so efficient that luxury consumption at the expense of other essential cations is a common occurrence. Magnesium deficiencies in apple trees and tomato plants induced by K have been discussed by Boynton and Burrell (1944) and Walsh and Clarke (1945), respectively. Similar observations of Ca deficiencies have been made; Lilleland and Brown (1939) found the absorption of Ca or Mg or both by prune trees to be decreased by the increased absorption of K after fertilization with potash. Bear and Toth (1948) concluded that since more than sufficient K will be absorbed by alfalfa if the exchangeable Ca is not relatively high, the more expensive nutrient, K, should be applied more frequently in smaller amounts.

*b. Release of Nonexchangeable Potassium.* Recent results indicating that Ca-saturated soils may release nonexchangeable K at a faster rate than their H-saturated counterparts (Ayres, 1949; Merwin, 1950) have been mentioned elsewhere (Section II.3*b*). York and Rogers (1947) found that saturating five acid-leached Alabama soils to 75 or 150 per cent with Ca increased the release of native nonexchangeable potassium during 150 days of moist storage; on the average, the 75 per cent soils released 27 per cent more K, and the 150 per cent soils 50 per cent more than did the H-saturated soils. By prolonged ladino clover cropping, Caribou loam limed with 3 tons of $CaCO_3$ per acre to about pH 6 released more K than the unlimed soil; a 10-ton application had no significant effect over that of 3 tons (Reitemeier, Holmes, and Brown *). At least a fraction of this increase was due to improved growth on the limed soil. Contrariwise, when McClelland (1951) incubated primary micas and feldspars with Ca and H bentonite, the rate of release of K varied oppositely as the exchangeable Ca : H ratio of the bentonite.

*c. Fixation of Potassium in Nonexchangeable Form.* It has been definitely established that alkalinity and liming increase the tendency of soils and clays to fix potassium in forms not immediately exchangeable. Some of the investigations, such as those of N. J. Volk (1934), G. W. Volk (1938), Attoe (1947), Stanford (1948), and Wiklander (1950), have been discussed in the section on fixation (Section II.4*b*). Gilligan (1938) treated electrodialyzed Chester loam and Sassafras silt loam with $Ca(OH)_2$ to provide Ca saturation of 0, 50, 75, 100, and 200 per cent.

The extent of fixation of the K of 0.4 me. of KCl when dried at 85°C. increased almost linearly as the degree of Ca saturation. For the Chester soil, the amounts fixed were 0.084, 0.113, 0.122, 0.149, and 0.203 me., and for the Sassafras soil, 0.055, 0.064, 0.069, 0.078, and 0.122 me. York and Rogers (1947) made six soils up to 0, 75, and 150 per cent or Ca saturation after acid extraction. During 80 days of moist storage, the Hartsells, Norfolk, and Dickson soils showed evidence of fixing small fractions of applications of 60 and 300 lb. of $K_2O$, the amount of fixation increasing between 0 and 75, and 75 and 150 per cent of Ca saturation. York (1949) observed that K fixed by Mardin silt loam during moist storage after liming was both available to alfalfa and extractable by $NH_4$ acetate of pH 4.8. His conclusion, based to a great extent on these results with one soil, that lime-induced fixation is of little significance as affecting the supply of available K, is similar to that of Attoe (1947). An increase in soluble silica as a result of liming was thought to support the idea that K is fixed as an aluminosilicate formed under alkaline conditions.

*d. Potassium Relationships of Naturally Calcareous Soils.* Gisiger (1936-37) compared $NH_4Cl$-exchangeable K and Neubauer K values of acid and alkaline soils. For acid or K-rich soils the exchange value exceeded the Neubauer value, but for alkaline soils deficient in K, the Neubauer value could range up to twice that of the exchangeable. From an extensive study of the behavior of K in naturally calcareous soils of Arizona, McGeorge (1933) concluded that they were relatively high in exchangeable and Neubauer K and exhibited no need for potash additions. As compared with noncalcareous soils, calcareous soils show relatively low water solubility of their K but a high availability of it to Neubauer seedlings. From noncalcareous soils, $CO_2$-saturated water extracted about the same amount of K as did distilled water, but far more from calcareous soils.

A situation with respect to K behavior differing from that of western calcareous soils prevails in naturally calcareous soils of certain parts of Illinois and Iowa. In 1930 Sears reported that plants growing on calcareous "alkali" soils of Illinois absorbed much less K than from the acid soils associated with them. The total K content of the soils was about 0.8 per cent. Displaced soil solutions of two soils from McHenry and McLean counties contained 0.1 and 8 p. p. m. of K, concentrations which are considerably lower than those of normal acid soils; the accompanying Ca and nitrate concentrations were very high. The Iowa high-lime soils have been studied intensively to learn the cause of their unproductiveness. Allaway and Pierre (1939) reported that in nine fields permitting comparison the unproductive and productive soils averaged 151 and 396 lb. of exchangeable K per acre. The former were generally higher in $CaCO_3$ content than the latter and had higher K fixation capacities. No real difference in rate of release of nonexchangeable K was found. Differences in exchange K levels may account partly for plant growth differences; soils containing more than 15 per cent $CaCO_3$ and less than 175 lb. of exchangeable K per acre usually produce K-deficient plants and respond to potash applications. On the basis of Sears' finding of low soluble K and high Ca and $NO_3$ in Illinois soils they postulated that the high Ca : K ratio also might decrease the absorption of K.

Stanford, Kelly, and Pierre (1942) thought that the 150-200 lb. of exchangeable $K_2O$ per acre on high-lime soils may not be readily available because of resistance to the liberating action of soluble Ca ions from the excess $CaCO_3$. To additions of 150 and 450 lb. of $K_2O$ per acre on high-lime Webster soil, corn and sorghum responded most, sweet clover did not respond, and buckwheat responded negatively (Bower and Pierre, 1944). This result was explained on two bases: (*a*) absorption of K from high-lime soils is repressed by high Ca and Mg concentrations and (*b*) crops requiring considerable Ca and Mg show lower response to K because they lower the Ca : K and Mg : K ratios in solution sufficiently to reduce repressive effects of Ca and Mg on K absorption. However, it was stated that the relationships between the amounts of nutrients absorbed from unfertilized normal soil were quite similar to those from high-lime soil treated with 450 lb. of $K_2O$ per acre. Since the exchangeable K content of high-lime soils is seriously lower than that of their productive counterparts, York (1949) was of the opinion that decreased absorption of K from highly calcareous soils such as these is due to a low level of exchangeable K, and not to antagonism by Ca.

### 2. *Ammonium Fixation and Its Relation to Potassium Fixation*

Although ammonium ions may affect the behavior and availability of soil K in various ways, e.g., the nutrient use of $NH_4$ by roots as a substitute for K (Jenny and Ayers, 1939), this discussion is limited to the fixation of $NH_4$ in a form similar to that of fixed K and the mutual dependence of fixed quantities of the two ions. In 1917 McBeth reported that no more than 81 per cent of the quantity of ammonium salt added to a California soil could be recovered after prolonged extraction by 10 per cent HCl. In additional studies seriously incomplete recovery of $NH_4$ by soils at 0°C., and the liberation, by grinding, of $NH_4$ fixed in field soil during 7 years of $NH_4$ applications were observed by Chaminade and Drouineau (1936) and attributed, along with fixation of K, to movement into the interior of crystals from the surface. Chaminade (1940) found that soil clays containing added $NH_4Cl$ lost appreciable amounts of exchangeable $NH_4$ when stored at 0°C.; e.g., of 0.516 mg. of N added as $NH_4Cl$, 0.476 mg. remained exchangeable after two weeks, and 0.350 mg. after six months. He concluded that (*a*) the loss was due to penetration of $NH_4$ into the crystal structure, (*b*) fixed $NH_4$ can exceed the exchangeable quantity, and (*c*) fixed $NH_4$ is unavailable to plants and microorganisms. Gruner (1949) was able to form an ammonium-mica from vermiculite by treatment with $NH_4OH$ and drying at 50°C.

Fixation of $NH_4$ by bentonite upon drying was observed by Page and Baver (1940) and Joffe and Levine (1947) but not by Wear and White (1951). Prior fixation of K or $NH_4$ had a depressive effect on the subsequent fixation of the other, both for bentonite (Joffe and Levine, 1947) and for vermiculite (Barshad, 1948).

Stanford and Pierre (1947) found a correlation coefficient of 0.87 between the moist fixation capacities of Webster high-lime soils for K and $NH_4$. The sum of fixed K and $NH_4$ for one soil when $NH_4$ was fixed first was 1 me. per 100 grams. When K was fixed first, the converse relationship held, except that the K-fixing capacity was 1.3 me. On the basis of these results, it was concluded that the two ions are fixed by the same mechanism. Peech (1948) has emphasized an effect in soils which can be explained by the same mechanism, namely, the pronounced blocking effect of ammonium ions on the release of nonexchangeable K. The choice of ammonium acetate as an extractant of exchangeable cations is therefore adduced fortunate for a sharp separation of exchangeable from nonexchangeable K.

Observations that the exchangeable Na content of western soils sometimes exceeds the cation exchange capacity as determined by adsorption of $NH_4$ led to the discovery of moist $NH_4$-fixation by some California soils (Bower, 1950). In general, the fixation capacity increases with depth of soil. For eight soils the amount of $NH_4$ fixed against replacement by sodium acetate, 0-6 me. per 100 grams, was close to the reduction in exchange capacity due to the fixation. In agreement with the results of Stanford and Pierre, the sum of fixation of $NH_4$ and K for a particular soil was constant, and the mechanism for the two ions must be identical. The extremely high fixation of K and $NH_4$ by these soils is currently attributed primarily to vermiculite in the silt and fine sand (Bower and Cady *). One result of these findings is the proposed substitution of Na acetate for $NH_4$ acetate in the determination of the cation exchange capacities of alkali soils (Bower, Reitemeier, and Fireman, 1952).

Two of these soils having fixation capacities of about 4 me. were so treated as to permit comparison of the availability of fixed and exchangeable $NH_4$ to nitrifying organisms and to Neubauer barley seedlings (Bower, 1951); the exchangeable $NH_4$ was supplied by satisfying the fixation capacity with K prior to the $NH_4$ addition. After 14 days, 80-90 per cent of the exchangeable, but only 16-30 per cent of the fixed $NH_4$ had been nitrified. In 17 days, barley absorbed $<10$ per cent of the fixed $NH_4$ but up to 75 per cent of the exchangeable. Allison, Doetsch, and Roller (1951) found that Harpster clay loam of Iowa (formerly high-lime Webster) can fix 1 me. of $NH_4$ when moist and about 6 me. at 100°C. drying. Usually less than 10 per cent of the fixed $NH_4$ was nitrified in 6-16 weeks. In this soil $(NH_4)_2SO_4$ normally is nitrified to about 60-80 per cent; when fixation was blocked by prior K or $NH_4$ fixation, nitrification increased to 90-100 per cent.

## IV. RELATIONSHIPS OF SOIL MICROORGANISMS TO SOIL POTASSIUM

In the preceding discussion, the role of microorganisms in the potassium economy of the soil has been slighted, however, their contribution remains vaguely defined. Specific importance of rhizosphere microflora in the liberation and delivery of K to roots beyond the effects of acids was not indicated by Clark (1949). Some attention has been given to the release of K of minerals and to the fixation of K in the bodies of organisms.

### 1. *Release of Nonexchangeable Potassium*

Koszelezkis (1909) grew *Aspergillus niger* on muscovite, biotite, orthoclase, and microcline. The fungus grew better on the two micas than on the two feldspars. Bassalik (1913) concluded that the intimacy of contact between organisms and silicate minerals is of greater importance than the nature of the excreted solvent. Thus, *Bacillus extorquens*, excreting only $H_2CO_3$, had the greatest effect because of close envelopment of the mineral. For the same reason, yeast showed the least solvent action. Under equal conditions of contact, bacteria producing organic acids, e.g., *Clostridium pasteurianum*, are more effective than those producing only $H_2CO_3$. The high solubility of powdered micas by *B. extorquens* was attributed to the pulverization into fine lamellae, thus presenting a larger surface than rounded particles.

The readily available K of sand, silt, and clay fractions and the long-time release from silt-size fractions of muscovite, greensand, and microcline as indicated by growing *Aspergillus niger* was determined by Eno and Reuszer (1951). More $NH_4$ acetate extractable K was found in the cultures than in the controls, and where large amounts of K were available, *A. niger* immobilized some by luxury consumption. The minerals varied as to both readily available and slowly available K, and the release increased with decreasing particle size.

Investigations of the possible importance of decomposing organic matter in the release of nonexchangeable soil K have been reported, but because of K added in the organic matter itself and of other confusing aspects, no conclusive evidence of substantial release by this mechanism has been forthcoming. The participation of both organic matter and microorganisms in this phase of the K cycle requires further elucidation.

### 2. *Fixation of Potassium in Microbial Protoplasm*

Kryopoulos (1915) found from studies of soil and liquid bacterial cultures receiving potash additions no evidence of the fixation of appreciable quantities of K. Vandecaveye (1924) reported the absence of fixation of K against $NH_4Cl$ extraction by clover hay and manure treatments. From studies of water-soluble nutrients of Aiken silty clay loam after treatment with (*a*) dextrose, $K_2SO_4$, $NaNO_3$, and superphosphate and (*b*) alfalfa, manure, and straw, Stephenson (1934) concluded that microorganisms retain nutrients but not to the extent of serious competition with plants. A non-nutrient material such as dextrose stimulates biological activity sufficiently to reduce the amount of nutrients, but the decomposition of organic matter containing N and other nutrients increases the soluble contents, especially of K. Sterilization by chloropicrin of a soil which normally fixed K did not reduce the extent of fixation (York, 1949).

Although these investigations clearly indicated no importance of fixation in microorganisms, others have been interpreted to support the opposite view. Feher and Frank (1936) observed that the values of citric acid-soluble P and K of forest soils were at a minimum in the summer and at a maximum in winter. The period of minimum availability coincided with that of maximum bacterial numbers and growth of vegetation. Aleksandrov (1950) attributed the major portion of K fixation and mobilization in sierozem and chernozem soils to microbiological processes. His evidence included an inverse relationship between available K and soil moisture content, a release of fixed K upon air-drying, and intensified fixation due to the presence or addition of organic matter. Hurwitz and Batchelor (1943) reported that Wooster silt loam to which sweet clover and oat straw were added to provide soil C : N ratios of 14-75 fixed K in a form not extractable by $NH_4$ acetate, up to 200 lb. of K per acre. The fixation was attributed to immobilization within microbial protoplasm; however, the possibility of occurrence of inorganic fixation was not even mentioned. The accumulation of a substantial quantity of potash in the bodies of soil microorganisms under average conditions is difficult to envision. Where water solubility is taken as the criterion of fixation, the possibility of adsorption of exchangeable K on the surfaces of bacteria (McCalla, 1940) should not be ignored.

Searches for the occurrence of fixation of K by soil organic matter, which can be considered apart from fixation by microorganisms, have usually yielded negative results. In a study of the availability of humate potassium, Jones (1948) found no indication of K fixation by humic acid. Martin, Overstreet, and Hoagland (1946) observed the fixation power of a soil to be almost destroyed by digestion with $H_2O_2$, but they assumed this could be a result of the acidity developed in the treatment.

## V. Effect of Aeration and Compaction on Availability of Potassium

The oxygen requirements of plants as supplied through the substrate have been extensively studied, especially by sand and water cultures. Some of these investigations have concerned effects on the absorption of various nutrient elements, usually including potassium. Loehwing (1934) grew sunflower and soybean plants in sand and in loam soil under forced aeration. In virtually all respects, aerated plants did better than control plants, except where very rapid aeration was applied. The aerated plants were larger and had a higher content of K expressed both as per cent K in the dry matter and as total K intake. Hoagland and Broyer (1936) concluded that the accumulation of salts by plants is associated with active aerobic respiration of the roots. Low oxygen or high $CO_2$ concentration of the nutrient medium may decrease absorption of ions such as K.

Chang and Loomis (1945) stressed that $CO_2$ toxicity should be included with $O_2$ deficiency as a factor of poor aeration. Carbon dioxide reduced the absorption of nutrient elements in this order: $K>N>P>Ca>Mg$. From some $CO_2$-treated roots, K was actually excreted. Reported high field contents of $CO_2$ exceed established toxic levels. Pepkowitz and Shive (1944) found that absorption of K, Ca, and P by soybeans and tomatoes was depressed by lack of sufficient $O_2$; however, K was less affected than Ca and P. They attributed the lesser dependence of K absorption on oxygen level to its greater mobility and different metabolism. According to Hopkins, Specht, and Hendricks (1950) both the top growth and the accumulation of major nutrients are dependent upon the $O_2$ supply to the roots of tomato, soybean, and tobacco plants. The accumulation of $K^{42}$ in the shoots of Marglobe tomato plants decreased with reduced $O_2$ content of the supplied air within the range 0.5-20 per cent of $O_2$.

Two investigations on Iowa soils have been reported which demonstrate a reduction in availability of K and other nutrients because of inadequate aeration induced by compaction, excessive moisture, and certain tillage practices. Corn grown on Fayette soil was much less deficient in K as indicated by visual symptoms and K content following plowing than after listing, disking, or subsurface tillage (Bower, Browning, and Norton, 1945). The initial exchangeable and water-soluble K contents of the soil of the different treatments were essentially equal. The corn yield on plowed soil was 18 bushels above the average by the other three tillage methods. Comparative results from plowing and subtillage of Webster and Clarion soils were similar to those on Fayette soil. The K results and corresponding N relations were attributed to better aeration of the plowed soil.

Lawton (1946) grew corn on Clarion loam and Clyde silt loam at two or three soil moisture levels and three degrees of compaction. Smaller plants were obtained under conditions of excessive soil moisture or high compaction. Although the contents of all the nutrients K, N, P, Ca, and Mg were reduced by some of these treatments, K was the only one thus affected by all. Forced aeration increased top and root growth and per cent K of the corn plants, but reduced the percentages of N, P, Ca, and Mg. Although the initial exchangeable K content would normally be adequate, application of K fertilizer increased growth and K absorption under the condition of restricted aeration. It should not be construed that an increase in soil moisture content within a lower range where aeration normally is not restrictive would result in reduced nutrient availability.

## VI. Movement and Distribution of Potassium in the Soil Profile

The total K content of soils in their natural state may increase, decrease, or remain virtually constant with increasing depth within a profile (Marbut, 1935). The actual distribution is dependent upon the homogeneity of the parent material with regard to type and abundance of K-bearing minerals, and the particular soil-forming processes involved. Thus, Joffe and Kolodny (1938) established that for certain podzolic soils the total K content and K-fixation capacity increased with depth, the B horizon being higher than the A. They attributed the higher total K in the B to the higher fixation capacity of its clay. With regard to immediate agricultural use, however, the distribution of available K may be regarded as more important than that of total K, and the discussion of K in the profile will be limited primarily to exchangeable and fertilizer forms.

### *1. Effect of Soil and Fertilizer Characteristics*

Ayres (1944) found that in the leaching of soils of initially high exchangeable K levels with 500 in. of water, the amount of K leached diminished with decreasing levels of K. The degree of saturation of the exchange complex with K appeared to be a more reliable index to leachability than the exchangeable K value expressed as pounds per acre. By the leaching the exchangeable K was reduced to about 30-80 per cent of the original content. At the conclusion of the leaching, the lower sections of the soil column contained more exchangeable K than the upper sections. Fireman and Bodman (1940) leached Yolo and Aiken clays intensively with distilled and $CaCl_2$-NaCl waters, followed by analyses of the soil columns by layers. The exchangeable K was reduced in both soils by the treatments. After leaching with the salt water, both soils increased in exchangeable K from the top to the bottom of the column, as did the Aiken soil following distilled water; after percolation of 66 in. of distilled water, the Yolo soil showed virtually constant exchangeable K throughout the column, which indicates that hydrolysis alone was less effective than bases in the replacement of K.

Volk (1940) measured the leaching of exchangeable K from Norfolk fine sandy loam, Hartsells very fine sandy loam, and Decatur clay during eight years of annual K applications of 10, 20, 40, and 80 lb. per acre. The two coarser soils lost about three to four times as much of the applied K from the surface 8 in. as did the Decatur soil. The percentage losses at the highest rate of application for the three soils were 34, 31, and 9 per cent, respectively. Kime (1943) observed that 16 in. of water leached out virtually all the exchangeable K and that of mixed fertilizers from Norfolk fine sand. The loss appeared to proceed at two rates, the initial higher rate being attributed to soluble fertilizer K, the second, slower rate to exchangeable and organic K. Meyer and Schneider (1940) studied the distribution of exchangeable K with regard to a compacted layer within the profile. They found that it tends to accumulate in the layer just above the compacted zone, and that when the fertilizer contains other salts, the mobility of K in the upper layers is greater, which increases the accumulation above the compacted layer.

By means of $K^{42}$, Henderson and Jones (1941) traced the movement of KCl equivalent to 600 lb. per acre applied to the surface of Bedford silt loam. With the infiltration of 2½ in. of water, only 5 per cent of the KCl penetrated beyond 1⅝ in. of soil, and the limit reached was about 3½ in. Andrews (1947) reviewed the effects of lime and fertilizer constituents on the leaching of K. Lime when mixed with the mass of soil conserves K from leaching, but the Ca of fertilizers applied in bands does not. When fertilizers contain large quantities of S, dolomitic lime should conserve the K supply more than calcitic lime, because of the high solubility of $MgSO_4$ and the consequent leaching of S as $MgSO_4$ instead of $K_2SO_4$. The action of S in band-applied fertilizer depletes the fertilizer K rapidly. Unused N of fertilizers tends to increase the leaching of both K and Ca.

### 2. *Effect of Plant Growth*

The pattern of vertical distribution of exchangeable K can be severely modified by the growth of plants. Lilleland (1932) determined the exchangeable K contents of soil samples taken at four 1-ft. intervals in 21 prune orchards. In all cases the values decreased downward, which condition was attributed to the extraction by the trees of K from a large volume of soil and a subsequent dropping of the leaves on the soil surface. With regard to the beneficial effect of winter legumes in retaining K from being leached below 8 in. in an eight-year period, Volk (1940) found that without legumes 9-32 per cent of the applied K was leached, and with legumes only 0-6 per cent. The average saving amounted to 17 per cent of the total applied.

In an investigation of the available K content of meadow soils, Jacob (1939) established that it was highest in the surface 0-3 in. layer, lower in the 3-6 in. layer, and in the 6-9 in. layer, averaged only about one-half of that of the surface layer.

Experiments by Gow (1939) on a Hawaiian soil suggested that the retention of applied K by acid soils which had a long history of $(NH_4)_2SO_4$ additions was unsatisfactory in the absence of vegetation, but much better when sugar cane was grown. However, under these conditions applications of K in excess of the crop requirements would not be expected to increase the exchangeable K content. Ayres and Fujimoto (1944) delineated three patterns of vertical distribution of exchangeable K in soils of Oahu, namely (*a*) decrease with depth, (*b*) decrease with depth to a point and thereafter constant, and (*c*) decrease with depth to 1½-2 ft. and increase at greater depth. Sugar cane had not substantially altered the natural pattern; about one-half of the K in the cane is left on the soil, and this, together with fertilizer additions, tends to keep the surface soil high in K. On the other hand, Napier grass depletes the surface soil of K because of the removal of the entire crop at four months' growth, and the profile becomes virtually uniform at a low level of exchangeable K.

## VII. EPILOGUE

The preceding discussion has been primarily directed to some of the more basic aspects of soil potassium. In those soils the potassium economy of which is somewhat complex, the mineral portion of the soil continues to appear to dominate the fixation and release of K. The proportional contribution of primary and clay minerals to the potassium supplying capacity of different soils requires further clarification. Some reports of the involvement of organic matter beyond that as one component of the cation exchange complex and as a source of K have been forthcoming, but the importance of such participation under ordinary conditions requires confirmation. The systems of equilibria and cycles among the various manifestations of soil potassium have become better understood in recent years, but the elucidation and prediction of the behavior of a particular soil remains to a great extent a matter of actual measurement.

A number of aspects of soil potassium problems, including some of importance in plant nutrition and in the production of crops in the field, have not been discussed in detail because of a purposeful orientation toward the fundamental principles of the chemistry of soil potassium. Among those omitted are the following: specific potassium requirements of various crops; the role of common organic additions as animal manures, green manures, residues, and mulches; correct usage of potash fertilizers; substitution of sodium for a fraction of the potassium requirements of certain plants; relationships to other nutrients such as nitrogen and phosphorus; erosion; and testing for potassium deficiency and fertilizer recommendation.

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# The Changing Pattern of Agriculture in England and Wales

J. A. McMILLAN
*National Agricultural Advisory Service,*
*Ministry of Agriculture and Fisheries, London, England*

CONTENTS

*Page*
I. The Period 1921-1938 . . . . . . . . . . . . . . . . . . . . . . . 165
  1. Farming against the Economic Background . . . . . . . . . . 165
  2. Changes in Farming Practice . . . . . . . . . . . . . . . . . 168
    a. Crop Production . . . . . . . . . . . . . . . . . . . . 168
    b. Animal Production . . . . . . . . . . . . . . . . . . . 170
  3. Agricultural Education . . . . . . . . . . . . . . . . . . . 174
II. The Period 1939-1945 . . . . . . . . . . . . . . . . . . . . . . . 176
  1. Organization for Wartime Production . . . . . . . . . . . . 176
  2. The Changing Countryside . . . . . . . . . . . . . . . . . . 179
III. The Period 1946-1950 . . . . . . . . . . . . . . . . . . . . . . 186
  1. Agricultural Policy . . . . . . . . . . . . . . . . . . . . . 186
  2. Recent Developments . . . . . . . . . . . . . . . . . . . . . 189
IV. Future Trends . . . . . . . . . . . . . . . . . . . . . . . . . . 192
  1. Technical Advances . . . . . . . . . . . . . . . . . . . . . 192
  2. Farm Buildings and Land Use . . . . . . . . . . . . . . . . . 194

This review relates mainly to the last decade and so covers a succession of years of unusual stress, a world war and the earlier years of an uneasy peace. It may be difficult, however, for those readers less familiar with the pattern of British agriculture to obtain a clear picture of recent developments without some understanding of conditions during the preceding period. With this in mind, a section of the review is devoted to a brief outline of agriculture in England and Wales from 1921 to 1938, and some comparative figures are included to illustrate certain wartime changes in land use and livestock production.

## I. The Period 1921–1938

### *1. Farming against the Economic Background*

In 1918, at the close of the World War I, prices of farm products were high, farming was prosperous, the importance of home food production seemed to be well established, and prospects appeared better than they had been since the depression of the 1870's. It was natural then that numbers of tenant farmers should consider the purchase of their farms as a good investment, and many bought at the then high values.

For those, and indeed all, who had a substantial interest in farming at wartime values, the year 1921 brought bitter disappointment. The Corn Production Acts (Repeal) Act, 1921, repealed the Corn Production Acts 1917 and 1920, and in its provisions showed quite clearly that there would be no extension of the wartime encouragement to grow grain. Its passage marked the beginning of a period of depression when the prices of farm products tumbled and confidence in the long-term future of farming was largely destroyed. This became apparent, even to a casual observer, in the general untidiness of the countryside, the neglect to repair buildings and fixed equipment, the cutting down of maintenance work on hedges and ditches, the falling down to grass of the poorer arable lands, and the farmers' instinctive unwillingness to spend money except on those enterprises likely to yield an early and reasonably sure return. There were still very large tracts of the better arable land and grasslands that were well farmed, but any long cross-country journey showed quite unmistakably that agriculture generally was in a low state.

The picture was not all black—it seldom is. There developed a stiffening resistance in many farmers, and sustained efforts were made to try out new means to meet high costs relative to low prices. The passage of the Agricultural Wages (Regulation) Act, 1924, which provided for the regulation of wages of workers in agriculture, focused attention anew on the importance of output per man as well as per acre and stimulated advances in mechanization. The farm tractor, which had been regarded as a rather costly and unreliable power unit during World War I, was greatly improved and became a more widely accepted aid to speedy and efficient cultivation. The milking machine found new supporters, particularly among the larger herd owners. More effort was concentrated on the better land.

It was in the middle 1920's that a new ray of hope came to the traditional arable farming areas. The British Sugar (Subsidy) Act, 1925, made provision for a subsidy in respect to sugar and molasses manufactured from beets grown in Great Britain. Few can have foreseen at that time the importance of this development on arable farming in the drier eastern counties where there was no salvation in grass. The substitution of a cash root crop—with valuable feeding by-products in the tops and the pulp—for the traditional turnips and other food roots that were costly to grow and could only be cashed through the animal, contributed greatly to preserve the balance of the arable rotation. It also assisted numbers of farmers to face the economic storm and to maintain their land more free from weeds and in a higher state of fertility.

Farming then in the 1920's might be termed patchy—a number of bright features here and there, but still a sense of insecurity as to the future. There was a tendency to turn away from those enterprises which made high demands for labor, unless the prospects of an early and reasonable return were good. Arable sheep disappeared from many light land arable farms; the practice of winter feeding bullocks in yards became less popular; the poorer arable lands and grasslands were somewhat neglected so that available labor might be concentrated on the better; farming profits generally were low, and in a number of cases only appeared on paper, for little or no allowance was made for the steady deterioration of buildings and equipment and for the neglect to maintain field drains, ditches, and hedges.

If the 1920's be called a period of depression, the 1930's might rightly be termed one of sober hope. Government action by way of subsidies, tariffs, and quotas, and the formation of Marketing Boards greatly helped to restore confidence in the agricultural industry. The Land Drainage Act, 1930, amended and consolidated the enactments relating to the drainage of land and indirectly drew attention to the very serious loss of production, which resulted from large areas of undrained or poorly drained land. The Wheat Act (1932) was an especial encouragement to the heavy land wheat farmer. It seemed almost too good to be true that growers of home-grown millable wheat were to obtain a standard price and a sure market for wheat through an Act of Parliament. And then the agricultural industry was further cheered by the Agricultural Marketing Acts 1931 and 1933, which enabled farmers to prepare schemes for the marketing of agricultural products and provided for the better organization and development of the agricultural industry.

Imported feeding stuffs were cheap and assisted particularly in stimulating the expansion of pig and poultry keeping, two livestock enterprises primarily dependent on concentrated feeding stuffs.

Generally, the 1930's were a period of rising wages and higher profits. There was still insufficient confidence to stimulate long-term improvements such as land reclamation, but a marked improvement in technical efficiency was apparent. Toward the close of the period, further encouragement came through the provisions of the Agriculture Act of 1937 and the Agricultural Development Act, 1939. Here was evidence that the country might again have to place more reliance on home production. There was a promise of security against substantial falls in the prices of certain farm products, of assistance to increase fertility and toward the plowing up of grassland. Further grants were to be available for land drainage; machinery reserves were to be established; a national service of veterinary inspectors was to be provided in the drive for eradication of animal diseases.

### 2. *Changes in Farming Practice*

*a. Crop Production.* This period saw the virtual disappearance of the steam engine as a power unit for cultivation, but a few sets were forced into short-term employment in the early emergency conditions of World War II. Though no large numbers of steam engines had been used in England, they had left their mark. What is now one of the best potato-growing districts was formerly shallow "sheep and barley" soil, capable only of being plowed to 4 in. Moreover certain areas of the most intractable clay soils would undoubtedly have remained unbroken and undrained but for their use.

While the steam engine was being laid aside, there came a gradual change from horse to tractor power. It might have been anticipated that the numbers of draft horses would decrease rapidly with the introduction of mechanical power for cultivation, but this was not so. The decline in numbers was steady but slow. Many of the smaller farmers continued to rely on the horse for lighter cultivations and for haulage and depended on contractors to carry out the heavier work.

It is not surprising therefore that implements and machines for horse draft continued to be used with tractors. The wear and tear was much heavier, the work was often carried out less effectively, for the implements had been designed to work at lower speeds; but there was little money available for the purchase of new tractor implements. There was, too, an inclination to wait until the newer implements had been under extensive test before any commitments were made for their purchase.

When agricultural prospects became brighter in the 1930's, implements and machines suitable for tractor operation were purchased more freely. Combine grain drills, for sowing grain and fertilizer in one operation, were seen more frequently among the range of implements on the larger farms; power-driven grain binders began to replace the older horse-drawn types. Later, combine grain harvesters came to be regarded with less curiosity and were accepted as valuable aids to the securing of the cereal harvest at lower costs. Their introduction, however, was slow and the earlier types, constructed for the harvesting of lighter crops than were common in this country, did not give the care-free service that had been anticipated. They are now looked upon as indispensable on the larger farms. Yet it is only a few years since there were serious doubts as to whether they could ever take a place in the harvest equipment suitable for this variable climate.

Other changes in mechanization worthy of mention were the introduction of the small tractor with sets of cultivating tools suitable for market garden work and of the power sprayer for use in fruit orchards. The interest in market gardening coincided with a period when prices of farm crops were low and prospects for vegetable production seemed brighter. The use of power sprayers became necessary as a higher proportion of the trees planted after World War I became too large for effective spraying with hand tools, and the importance of spraying technique in the production of high quality fruit was more widely recognized.

Fertilizer practice changed but little during the period. In the late 1920's it was estimated that rather less than one-third of the farmers used fertilizers. The remainder relied mainly on farmyard manure.

Permanent grassland, if fertilized at all, might receive dressings of from 5 to 10 cwt. (560-1,120 lb.) per acre of a phosphatic fertilizer at intervals of four or five years, but even this practice became less common owing to the uncertainty of a profit from the livestock that might graze the improved sward.

The introduction of the combine grain drill undoubtedly awakened interest in the use of fertilizers. Granular fertilizers, which would run through the drill more freely and without bridging, began to appear on the market. The marked responses of certain cereal crops to suitable fertilizers placed near the germinating seed focused attention not only on the value of placement but also on the possible benefits likely to arise from the extended use of fertilizers. Even among the oldest farmers, whose reliance had been centered on farmyard manure, there was a reluctant but noticeable acceptance of the fact that fertilizers could be used as a valuable supplement to obtain higher crop yields.

In 1920 the number of named potato varieties ran into four figures. The position was little better in respect of other farm crops. There were very few reliable experiments to guide the farmer on the choice of varieties suitable for different soils and climatic conditions, and he had to rely largely on his own knowledge and any information he could glean from the experiences of his near neighbors.

Clearly, there was the need for some independent authority to sort out various synonyms and to carry out accurate yield experiments. Fortunately, this was quickly realized and, through the efforts of a band of pioneers, the National Institute of Agricultural Botany was chartered in 1921 to carry out these and kindred tasks. In the briefest terms the Institute's objectives might be stated as better seeds and crop improvement. This is not the place to describe the Institute's organization and many interests, but by way of illustration reference may be made to two important features of its work. By 1938 the long labors of its Potato Synonyms Committee had resulted in the reduction of the hundreds of named potato varieties to a mere twenty or so of recognized commercial value, and a procedure had generally been accepted for the systematic testing of new introductions. Another section of the work related to the collection and testing of established and new varieties of cereals both home bred and imported from abroad. A trial system was evolved whereby the most promising varieties could be tested at the farms of the Institute or its substations. The plant breeder and other introducers of new varieties thus had an opportunity to subject their most promising selections to an independent body for test alongside the older established sorts. In these two directions alone the Institute's work had been striking and was to prove of great value in the war years that lay ahead.

Progress in the sorting out of varieties of vegetables was slower and indeed rather discouraging. The problem of synonyms was known to be one of great complexity, and under prewar conditions there seemed to be no easy road to its solution.

In fruit production, the work of the East Malling Research Station in introducing and testing new types of root stocks for top fruit merits special mention. Stocks were raised suitable for various soil conditions and to encourage earlier bearing and were largely used in the planting up of new orchards. Results so far have indicated their usefulness in comparison with the older and more late-maturing sorts.

A number of new plantations of soft fruit, made when arable farming was less attractive, failed rather badly because of the inferiority of the stock. There was uncertainty as to its quality and freedom from disease, and a prospective grower could obtain little information to guide him in his choice. The introduction of certification schemes for soft fruit, operated by the Ministry of Agriculture, did much to ensure that new plantings should be made with approved stocks free from certain serious pests and diseases.

At this time too there was a development of the glasshouse industry for the production of tomatoes, cucumbers, and lettuce. Others, who found the returns from more common farm crops inadequate, turned to flower growing, and in certain selected districts it was not uncommon to find each farmer devoting at least a small part of his arable land to perennial flowers.

*b. Animal Production.* The Livestock Improvement Scheme, 1914, though introduced with troublesome times just ahead, was eventually to exert an important influence on livestock improvement. Under its provisions grants could be made to individual farmers or to societies owning good quality bulls or boars, who were prepared to allow those sires to be used communally. The response was so satisfactory that by 1930 grants were being made in respect of some 1,500 bulls and 1,000 boars. The smaller farmers in particular were strong supporters of the scheme.

They saw in it the opportunity of obtaining the service of good sires at a moderate cost, and many of them had insufficient livestock to justify the keeping a sire of their own. There is little question that the quality of the progeny was much improved through this use of better sires. Moreover, the grouping of farmers into societies under the scheme stimulated discussion and led to the adoption of better methods of management.

Grants to societies for milk recording were taken up much more slowly, but by 1939 some 200,000 cows in 5,000 herds were being recorded under the official scheme.

One of the important developments of the period followed the introduction of the Improvement of Livestock (Licensing of Bulls) Act, 1931. Owners were required to apply for licenses for all bulls attaining 10 months of age. Inspections were carried out by livestock officers of the Ministry of Agriculture. Those bulls approved were licensed, those rejected were required to be castrated or slaughtered, unless a permit was given for their retention for a limited period. At the time of its introduction there were many predictions of the disasters such a drastic regulation might bring in its train, but it was quickly realized that the benefits were likely far to outweigh the possible disappointments of individuals. The owner of a rejected bull had a right of appeal. The bull was then inspected by an independent referee, whose decision was binding both on the owner and the Ministry. None now doubts the necessity for this Act, which aimed at the elimination of the scrub bull. Regulations under the Act are continuously under review, and changes are made when they are thought desirable.

Milk prices in common with other farm commodities had fluctuated widely not only from year to year but from season to season during the 1920's. Summer prices were always lower than those of winter, but in certain summers of plentiful grass milk became so plentiful that a proportion was left on producers' hands. Clearly, there was need of some stabilizing authority to protect both the consumer and the producer.

The setting up of the Milk Marketing Board in 1933 was really a first step to order out of chaos in milk marketing. Its early years were critical ones, for acute problems of surpluses had to be solved by an organization with little experience. These storms were weathered, and confidence grew both in the Board and in the prospects of milk production as a farming enterprise. Many farms changed over to milk production from rearing or fattening, and numbers of established milk producers enlarged their herds. There was more certainty of a reasonable and regular return from milk than from beef, and it was not surprising to find numbers of covered yards holding dairy cows, milked in an adjoining milk parlor, where earlier it had been the practice to feed stores or fatten beef cattle.

This gradual switch to milk production continued up to 1938 with a tendency to change from the general-purpose breeds to those of dairy type, such as the British Friesian, Ayrshire, Jersey, and Guernsey. The emphasis was on winter milk for liquid consumption, produced largely from imported feeding stuffs.

Though official milk recording made slow progress, many producers recorded privately as an aid in the feeding of their herds. The earlier practice of feeding all cows alike was gradually replaced by a system of feeding according to yield. Much more attention was given to the preparation of the dry cow for her lactation, the control of bulky foods to the high yielder, the requirements for mineral supplements, and the better utilization of summer grass.

Sheep numbers fell very sharply between 1914 and 1918. The losses were mainly in the arable districts where the high demands of arable-land sheep on labor and for tillage crops had been met only with difficulty under wartime conditions. This decline in numbers continued. Slowly but steadily flock after flock of ''arable'' sheep was dispersed, until the few remaining were almost entirely special-purpose flocks of Down breeds kept primarily for the breeding of rams for sale.

Though grass flocks became rather more mixed in type—cross-bred rather than pure breed ewes—more care was given to their management. Various pining diseases, which earlier had seldom been diagnosed, were the subject of investigation, and such practices as dosing against worm infection and the supply of mineral licks were adopted more widely. There was, however, little general enthusiasm for sheep. They were regarded often as scavengers to follow the cattle in their rotation round the grass or to consume the by-products of arable land.

On the hill farms where hardy mountain sheep contributed most of the farm income, the period was marked by uncertainty. The menace of bracken fern became more serious; in some areas there were fears that some of the land might be taken for afforestation; farm incomes were so small that there was little available rent income to enable the landlord to make repairs and renewals and equally little for the tenant to effect schemes of improvement. Generally then, hill farming was at a low level, and few could see any much better prospect ahead.

Pig production fluctuated through fairly definite cycles. High prices attracted more interest in pigs and the pig population increased; pig prices then tended to fall, and so would the number of pigs. In consequence, there was a high peak and a low trough of pig production roughly every four years. This variation was much less marked after the establishment in 1933 of the Pigs Marketing Board, whose responsibility lay with the marketing of bacon pigs. Pigs for pork were still a free market, a factor which made it less easy for the Board to establish a stable pig market. There would, however, have been strong opposition to any scheme of controlling the marketing of pork pigs under peacetime conditions.

Great improvements took place in the breeding, management, and feeding of pigs during the period. In breeding, greater regard was paid to the merits of strains within a breed. At the same time the Livestock Improvement Scheme, 1914, was exerting an influence on producers to use pure-bred boars of good type. Indoor farrowing, not free from serious losses in young pigs under cold and damp conditions, gave place particularly in the south of the country to the keeping of sows on free range. The value of a good start for young pigs through creep feeding was more generally appreciated.

Before the setting up of the Milk Marketing Board, skimmed or whole milk was included in the ration of many pigs. Later it was seldom used. This change created difficulties for those who took little care to balance their meal rations and include essential protein foods. The very fact, however, of the withdrawal of milk products for pig feeding created interest in suitable substitutes, and better balanced rations were being fed in the years just before the war. Credit for part of this improvement was due to the Bacon Development Board, set up under the marketing scheme to stimulate educational and experimental work on pig production. The Board also created a growing interest in pig recording and litter testing, but these developments were interrupted by the outbreak of war.

Poultry keeping came to be regarded as a popular form of small-scale farming. It attracted quite a number of ex-service men of World War I and others who desired an open air life but had too limited capital to enter into general farming. Poultry numbers increased rapidly both on general farms and on newly created specialist poultry farms. Unfortunately, expansion was rather too rapid, and there were too many inexperienced buyers. Inferior stock was used more commonly to breed replacements and birds for sale, and as a result there was much disease and heavy death rates.

Clearly some tightening of breeding standards was necessary, and a truer appreciation of the value of good rearing for pullets expected to stand up to the strain of high production in later life. It was with these objects in view and also to provide sources of good poultry stock that the Ministry of Agriculture introduced the Accredited Poultry Breeders Scheme in 1933. Breeders who wished to enter this scheme and to be accepted for the approved register were required to conform to certain rules, including the blood testing of their stock for pullorum infection and the elimination of reactors. As the scheme became more widely known, more and more breeders were accepted, and a higher proportion of eggs for setting and of stock for sale came from these farms. Experience has proved the scheme to be of the highest value, not only to the commercial producer but also to the many thousands of small "domestic" producers who require stock replacements from year to year.

Improvement then in poultry husbandry was due chiefly to breeding from better stock with less risk of disease, but there were also advances in feeding practice, particularly on the specialist poultry farms. Better-balanced rations were fed to birds in production, and much greater care was taken to rear young stock on clean ground and to avoid any check in growth.

### 3. *Agricultural Education*

The responsibility for preparing and carrying out schemes for agricultural education lay with the sixty county councils. There was no statutory obligation placed upon them to organize schemes, but they were encouraged to provide training for young people interested in rural pursuits and also advice for farmers and horticulturists. As an inducement Ministry of Agriculture grants on a liberal scale were available to meet approved expenditure.

Few counties had appointed organizers of agricultural education before World War I, but the experience of those counties which had made such appointments stimulated a further number to take action during the 1920's. By 1938 every county had made an appointment and in many a number of assistants had also been recruited, particularly where the organizer was also the principal of the farm institute (farm school), and a teaching staff was therefore necessary.

The organizer's staff varied both as to training and numbers according to the special needs of the county and in relation to the interest of the county council in agricultural education generally. It comprised assistants in general agriculture and horticulture and also officers especially qualified in such subjects as dairying, poultry husbandry, and rural domestic economy or home economies.

The counties of England and Wales were grouped to form eleven provinces. A university or agricultural college was selected as the provincial center, and a number of the teaching staff at those selected centers were available to give specialist advice to the county staff and to assist in solving the more difficult problems. The services of a soil chemist, plant pathologist, entomologist, bacteriologist, and agricultural economist were generally available at all centers.

It is difficult to describe briefly how the county service operated. The development of a scheme of agricultural education was essentially a matter for each county council and, though the Ministry of Agriculture gave general guidance, this was not always accepted. In one county, chief emphasis might be placed on the organization of day classes for rural boys and girls over school-leaving age. In another, the staff might concentrate more on advice to farmers, and the diary of each member might show as much as 80 per cent of his time spent on such work. In still others, for example, in dairying counties, a larger proportion of the staff might be women, who would devote their attention chiefly to problems in dairy management and the improvement of the keeping quality of milk.

The system had definite merits, in that a number of methods of translating the findings of research into farm practice were tried out simultaneously. Questions of organization and of methods could be discussed at annual conferences and, where thought desirable, changes could be made in the light of experience. There was a wide field to cover, and the number of staff was all too few, but valuable work was done in the classroom, the field, the dairy, and by demonstration, show exhibit, and field experiment. The highest praise of the service came from those who made most use of it.

It was unfortunate that the staff came into contact with only a small proportion of those it had been appointed to serve. The progressive farmer, the specialist horticulturist, and the keen poultry keeper were those who repeatedly called for advice and wished to be kept informed on the latest research work. Many others never asked for advice nor attended lectures or demonstrations. Yet there was no right of entry to their farms or holdings, even if it was apparent from the hedgerow that these would be likely to benefit from an advisory visit. This indeed is one explanation why newer methods were taken up but slowly. Such thoughts prompted certain county councils to concentrate the activities of their staff on classes for the young people. They saw that the best approach to the farmer, who would not seek for advice, was through the younger generation, perhaps through his son or daughter. It was quite remarkable how effective this approach proved to be, and indeed today it is one of the important benefits to the industry arising from the Young Farmers Club movement.

Rather more systematic training was possible at farm institutes (farm schools). The course covered a year and about half each working day was spent in practical training on the institute farm. The aim was to give a better training for future farm workers so that they might do their jobs more intelligently and possibly fit themselves at a later date for posts of greater responsibility. Many of those attending had been awarded Ministry of Agriculture Scholarships for the sons and daughters of agricultural workers under a scheme introduced in 1921. It is surprising how many of these selected scholars have made good. A few qualified for further awards, took university degrees and now hold responsible agricultural posts in the government service and in commerce.

## II. The Period 1939–1945

### 1. *Organization for Wartime Production*

There is little doubt that the speed and confidence with which the plan for home food production was introduced were important factors contributing to its success. The outlook in 1939 was very different from that in 1914. In the earlier year, few believed that home food production could have any appreciable effect on the wartime effort. This uncertainty and the limited availability of mechanical power prevented the drive for increased food production from gathering its full momentum until the closing years of World War I. In 1939, on the other hand, older people still retained vivid memories of the submarine menace of 1917 and 1918, and there was no hesitation in deciding that agriculture, in common with other industries, must enter upon active service as quickly as possible.

Plans had been made for the appointment of a War Agricultural Executive Committee for each county in England and Wales in the event of an emergency. As in the earlier war, county committees were to act as the agents of the Minister of Agriculture in carrying out the government's food production policy in their respective counties and to provide a link between the Ministry's headquarters in London and the farmer.

Each committee included representatives of landowners, tenant farmers, farm workers, and agricultural scientists. Each executive officer was technically trained, usually the organizer of agricultural education or the county agricultural officer of a county council.

Land Commissioners of the Ministry, each covering two or three counties, were available to give advice on land agency matters and for consultation on the many administrative problems arising in the work of a wartime organization.

On the outbreak of war, committees soon settled down to work. The Ministry of Agriculture quickly decided its program, which in the early days might briefly be stated as the maximum production of wheat, barley, oats, potatoes, and milk with the greatest possible self-sufficiency to meet the food requirements of ruminant livestock. It was realized that pigs and poultry would make large competitive demands with dairy cattle for concentrated feeding stuffs, and warning was given that pig and poultry numbers must be drastically reduced.

The first major problem for each county committee was to decide, in the light of the objectives announced by the Ministry, how its particular county could best assist in the attainment of that program.

Clearly no uniform line of action was possible. The best hope of higher crop production from a county already largely arable lay in the raising of the level of production on the existing land through better field drainage, more timely cultivations, liming where necessary, and more generous application of suitable fertilizers. In a county largely grass, clearly the plow-up program was the more important, but this was no easy task. Many of the mainly grass farmers had no suitable tractors or implements. Neither they nor their workers had knowledge of arable farming practices. Further, few grass farms were equipped with suitable storage accommodation for the produce of arable crops.

The first progress reports to the Ministry from the county committees brought to light definitely the type of outside assistance deemed necessary for higher production. In some it was higher-powered tractors for contract plowing; in others mole-draining plows; in others seed and fertilizer drills; in still others more labor, especially drawn from workers skilled in tractor plowing and the crafts of arable farming. It was evident at this stage that it would be necessary in all counties to set up servicing departments, and before long each county was able to offer farmers a machinery service—for plowing, draining, cultivating, and harvesting—and a gang labor service to supplement the normal farm staffs for special work, e.g., scrub clearing and major schemes of ditching and land drainage. This labor was also available to assist in harvesting.

Everyone worked with energy and enthusiasm—committee members, district committees members, parish representatives, staff, farmers, and farm workers. The face of the countryside changed very quickly. Demands for new tractors, implements, machines, feeding stuffs and farm requisites of all kinds rapidly outgrew the restricted supplies. In such circumstances, the best use of these requisites was only possible through intelligent control, and so, much as it was regretted, controls had to be applied.

This decision led in turn to new administrative duties being placed on the county committees, the allocation of imported tractors and implements, so that those in most urgent need received priority in delivery;

the rationing scheme for feeding stuffs and for fertilizers; the permit system for the host of farm requisites that were in short supply. Mistakes in allocation there were. How could it be otherwise? Looking back, however, few will question the wisdom of imposing controls or will criticize the impartial way in which applications were reviewed.

It certainly was a change for many farmers to receive coupons for a strictly limited amount of the same types of feeding stuffs which a few years earlier had been cheap and plentiful. They were now used with greater care.

Many farmers had used little or no fertilizers in prewar years. Now crop prices were high, the nation needed all that could be produced. Why was it that the rationing scheme provided such a meager allowance? It was surprising to find that with little or no prompting practically every farmer took up and used his full allocation, based on the particular crops to be grown, with a small reserve for soils exceptionally deficient in phosphates or potash. It was quite evident that the fertilizer rationing scheme had done much to broaden interest and knowledge in balanced manuring, and even now in a free market the greater proportion still use some fertilizer, though higher rates of application could be given with advantage on a number of farms.

As the responsibilities and scope of the work of the county committees grew, so it became necessary to increase the staff. The executive officer of each committee in most counties was a county council officer loaned for wartime duty to the Ministry of Agriculture. Practically all his technical staff, except those called for active service in the forces, were also loaned to the Ministry of Agriculture. Assistance was also available from many of the teaching staffs of agricultural colleges and universities, In addition it became necessary to recruit numbers of administrative and semi-technical officers for the land drainage, farm machinery, labor, supplies control, and other branches of the county work. So the county committees were supported by a staff drawn from a number of sources. It was the aim to utilize the services of all who, by training or experience, could contribute to the united effort.

The association of a large body of voluntary helpers from the agricultural industry and of the staff worked very well. Committee members were prepared to spend long hours on inspections and in conference, and their guidance made the task of the staff much less difficult. Without this voluntary assistance it is certain much less could have been accomplished. Certain county crop targets would have been difficult to secure, and in the few cases where action became necessary on the grounds of bad husbandry, it was reassuring to the whole industry to know that the investigations had been conducted by farmers of high repute.

In the war years when speed was so essential, it was necessary to give county committees wide powers, but on certain important questions they could only make recommendations for the Ministry's action. For example, a tenancy could not be terminated nor an owner-operator dispossessed, except by the Ministry, and no such action was taken without the fullest investigation. Normally such cases came to notice only when the occupier persistently declined to comply with orders to grow specified acreages of certain priority crops or to plow up a reasonable proportion of his grassland. These and other rather drastic powers under the 1939 Defence Regulations and various orders made under these regulations were disliked intensely, but were accepted as necessary in a critical emergency. That they worked so smoothly is a tribute to the many farming members of county committees. Indeed, it would be very difficult to pay adequate tribute to their voluntary work or to assess its importance in the success of the campaign.

## 2. *The Changing Countryside*

The story of higher production is in reality a description of the work of three M's—master, man, and machine. No one would dispute the value of overall planning and the help of the scientist and adviser, but those who contributed most to the changing countryside were the willing farmer, the tireless farm worker, and the improved tractor and implement.

The picture can be seen more clearly through a few illustrations which allow of a comparison with earlier peacetime production. Figure 1 gives a record of the acreages of permanent grass, temporary grass, and tillage over a series of years. Before 1939, the acreage of permanent grass in England and Wales remained around the 15,500,000 mark, that of temporary grass just over 2,000,000, and that of tillage about 7,500,000. From then onwards there was a steady increase in the acreage of tillage at the expense of permanent grass up to the peak year of 1944. In the latter year, permanent grass had been reduced to around 9,500,000 acres, temporary grass was about 3,000,000 acres, and tillage had increased to over 11,500,000 acres, representing a decrease of 39 per cent in permanent grass and an increase of 53 per cent in the land under tillage.

Not all the permanent grass was easy to plow. It varied from roughish swards on heavy "ridge and furrow" land to poor thin grass on soils of "blow-away" sand. Much of the heavier land was waterlogged in winter, lying in fields surrounded by tall wide hedges and blocked ditches. Each field presented its own particular problems. In some instances hedging, ditching, and mole draining had to be carried out before plowing; in others the roots of bushes had first to be removed; in others the grass mat was so thick that severe disking had to precede any attempt to make a satisfactory job with the plow. Then there were liming and phosphate problems, for much of the older grass had remained unfertilized for many years. Experience in the earlier war had shown also that wireworms were often lurking in the rotting grass sods and could ruin susceptible crops in a short time.

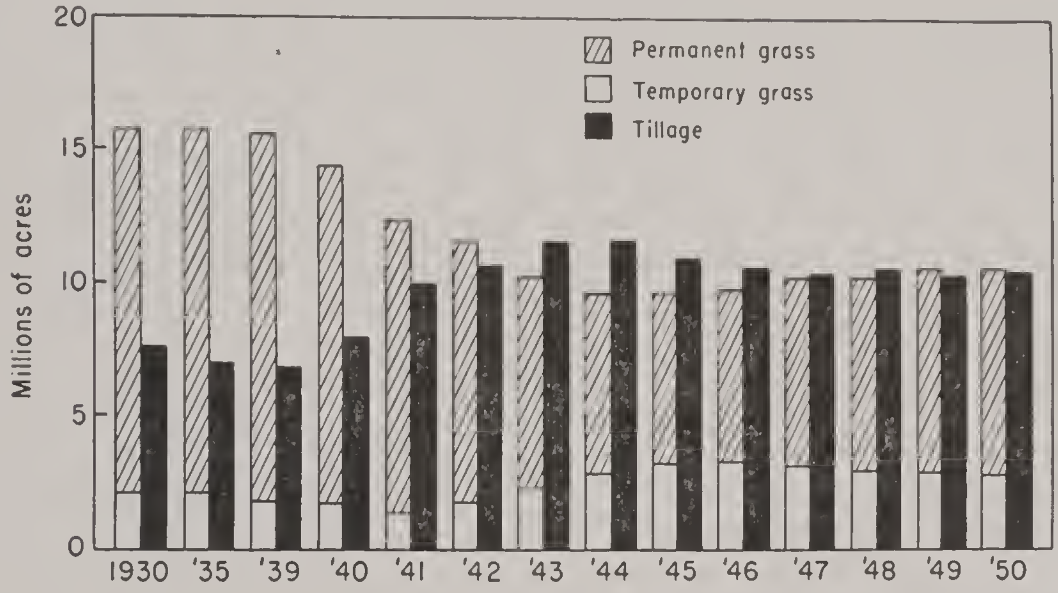

FIG. 1. England and Wales. Acreages of permanent grass, temporary grass and tillage in 1930, 1935 and from 1939-1950.

Mechanically the task became easier with the import of crawler and other high-power tractors, heavy disks and plows of the stump-jumper and prairie-buster type. Home machinery production was expanding to meet essential needs in light tractors, ordinary and mole-draining plows, drills, and manure distributors. Here one acknowledges the big part played by both imported and home-produced machinery. How impossible it would have been to have contemplated work on this wartime scale without it.

Figure 2 shows the acreages of wheat, barley, oats, and potatoes in 1930, 1935, and from 1939 to 1950 and gives an indication of how high a proportion of the tillage area was occupied by these four crops. For example, in 1943 they covered almost 8 million acres or 72 per cent of the total tillage area.

Between 1930 and 1935 the wheat acreage rose 400,000 acres largely because of the better security provided under the Wheat Act, 1932. From a figure of 1⅓ million acres in 1939, it rose to 3¼ million acres in 1943, the peak year. Since then the area sown has fluctuated around the 2-million mark.

With barley, the increase in acreage was less pronounced. The pre-war figure of 900,000 acres increased steadily until it topped the 2-million-acre mark in 1946. Barley growing extended far beyond those soils which had established a reputation for good quality malting barley. Indeed, it was surprising how many excellent samples were obtained from unpromising soils.

The oat acreage rose from 1½ million acres to 2½ million in 1942 and continued at about the 2-million level for the remainder of the period.

The climb of the potato from 500,000 acres to rather more than double that figure in 1948 appears much less spectacular on paper, but it was in fact a big achievement. From a yield viewpoint it would have been an advantage if the bulk of this increase could have been found on the rich soils in the main potato-growing areas. Root eelworm troubles in certain of these areas made it unwise to press there too strongly for additional acreage. A high proportion of the increase had to come from many new growers who were required to introduce a few acres in the normal root break in their rotations. Many of the latter had little experience of the crop and, until contract work became well organized and experience reduced a few common mistakes, yields were rather disappointing.

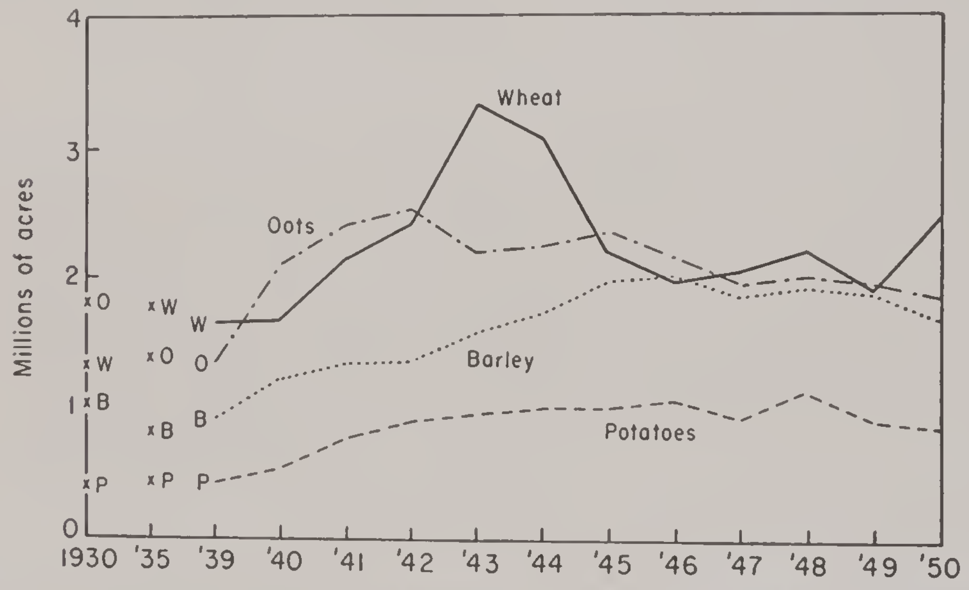

Fig. 2. England and Wales. Acreages of wheat, barley, oats and potatoes in 1930, 1935 and from 1939-1950.

The foregoing paragraphs have indicated how rapidly the industry switched toward arable farming. Possibly a greater achievement was the securing of higher yields per acre. In spite of the inexperience of new growers and the many adverse factors that had to be overcome, it is surprising to record higher yields per acre for all four crops. This is shown in Table I.

TABLE I

Average Yields per Acre of Corn Crops and Potatoes in England and Wales

| Ten-Year Periods | Wheat |  | Barley |  | Oats |  | Potatoes |  |
|---|---|---|---|---|---|---|---|---|
|  | cwt.[a] | bu.[b] | cwt.[a] | bu.[b] | cwt.[a] | bu.[b] | tons[c] | bu.[b] |
| 1920-1929 | 17.7 | 33.0 | 15.6 | 36.4 | 14.5 | 50.7 | 6.2 | 231 |
| 1930-1939 | 17.8 | 33.2 | 16.2 | 37.8 | 15.8 | 55.2 | 6.6 | 246 |
| 1940-1949 | 19.1 | 35.6 | 17.8 | 41.5 | 16.9 | 59.1 | 7.0 | 261 |

[a] 1 cwt = 112 lb.

[b] Bushel equivalents calculated on basis of 60 lb. wheat, 48 lb. barley, 32 lb. oats, and 60 lb. potatoes.

[c] Long tons of 2,240 lb.

With the major part of the tillage acreage set aside for wheat, barley, oats, and potatoes, what of the remainder? Sugar beet was grown up to the capacity of the sugar factories, and its by-products were more highly valued, for other feeding stuffs were in short supply. Beans and peas were grown on a higher acreage to provide more protein. Vegetable production, particularly of winter greens and carrots, extended from the market-garden areas to the general farm in suitable districts. Glass-house production of out-of-season crops was encouraged through a fuel allocation, conditional on a minimum percentage of the covered area being devoted to essential food crops for sale.

The hum of the internal combustion engine penetrated to all but the inaccessible upland areas. Harvest time in the leading grain-growing districts brought a change of scene. As the combine harvester and straw baler became more common, it became harder to find those long rows of grain shocks, so long a pleasing picture of the English harvest field.

In the potato and sugar-beet growing areas too, changes were taking place. The earlier types of harvesters were being adapted to suit varying soil types. There was promise here of progress, a hope that before long the back-aching job of harvesting these two crops might be eased.

As the plowing-up program progressed, there was a smaller grazing area for an increasing number of cattle (Fig. 3), for the ley acreage only increased by a million acres while that of permanent grass fell five times as much. Here then was a problem. How were the increased numbers to be maintained? The answer was found through experience. The temporary leys, many sown with improved leafy strains of grasses and clovers, proved more productive; the wastage that had resulted when too much grass was available was much reduced; smaller well-drained fields provided better grazing than those larger and waterlogged; piped water supplies enabled the grazing of acres which previously had been reserved mainly for hay. Production and utilization could have been even better had there been a sufficiency of phosphatic fertilizers, but supplies were too small to allow reasonable applications to both arable land and grassland, and the latter had to go short. The grazing problem was eased somewhat by a decrease in sheep numbers, but almost as many stock units were carried on the smaller acreage—to many quite a surprising achievement.

Milk production was given high priority even though there were prospects of only limited supplies of imported feeding stuffs. It was decided that as high as possible a proportion of whatever was available should go to the dairy cow, so a drastic reduction in pig and poultry numbers was called for. The former fell from 3½ millions in 1939 to 1⅓ millions in 1943, and the latter from 56 millions to 29 millions in the same years.

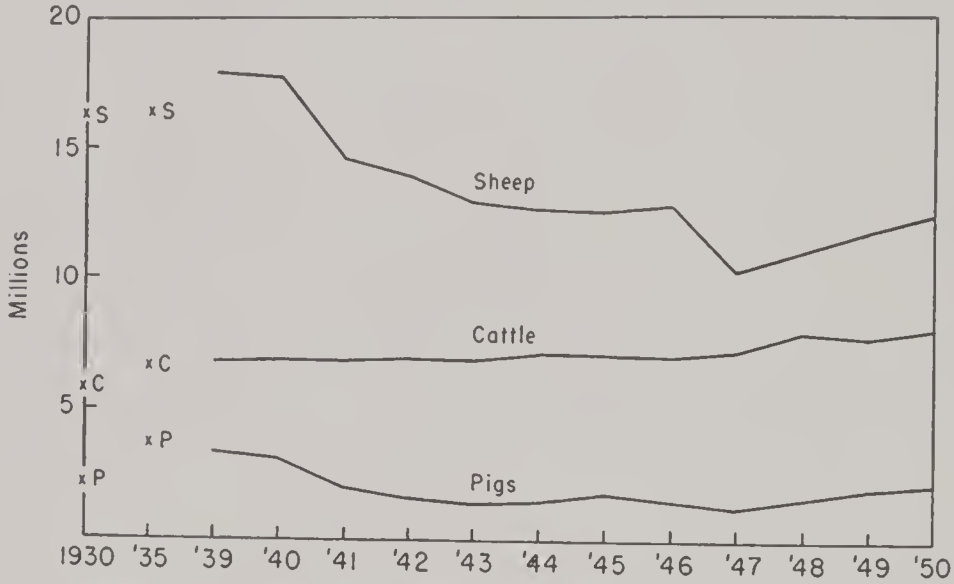

FIG. 3. England and Wales. Numbers of cattle, sheep and pigs in 1930, 1935 and from 1939-1950.

There were four directions in the drive for higher and better milk production that merit comment: (*a*) the provision of adequate and suitable home-grown foods to replace a substantial part of the imported concentrated feeding stuffs formerly available, (*b*) better management of the grass, (*c*) a partial switch to dairy breeds and the use of better sires, (*d*) disease control.

So much of our winter milk had been produced from imported feeding stuffs that the new situation demanded a substantial change in feeding practice for most dairy farmers. The bulky foods that had been thought of chiefly for maintenance were examined again. Good quality hay could provide much more protein than hay overripe and badly harvested; silage was another and less wasteful way of saving surplus grass, and on most farms there was overabundance during the early summer flush of May and June; marrowstem kale could supply substantial amounts of protein and starch equivalents per acre; more home-grown oats and beans or peas, mixed in suitable proportions, would replace balanced oil meals. More regard was given to the planning of the farm cropping for priority crops and milk production and to working out suitable rations of home-grown foods. The very fact that the system of feeding was changing stimulated interest in rationing.

The rather more stable market for milk, following the setting up of the Milk Marketing Board, had begun to exert an influence on the breed or type of cattle on many farms. Statistics available through bull licensing indicated that in the late 1930's, the Ayrshire and British Friesian were making headway. Later, the figures suggest an even more rapid changeover. For example, the number of Ayrshire bulls licensed in 1942 was double that in 1936; in the British Friesian breed the increase was treble during the same six years. Any relative figures for later years would be difficult to interpret because of the introduction of artificial insemination. Two trial insemination centers were set up at Cambridge and Reading in 1942. and in the following year regulations were made under an Agriculture Miscellaneous Provisions Act allowing for the operation of other centers under license. The development initially was slow, and artificial insemination cannot be said to have had any effect on wartime production. It did, however, create interest in breeding problems and tended to make a number of farmers more disease conscious.

Much could be written on disease control, but here it is intended to refer shortly to two aspects. Under war conditions it was not possible to carry out quickly the plan toward the eradication of tuberculosis, but testing was still carried out. Under the circumstances good progress was made in establishing new clean herds.

In another direction encouraging results were being obtained through the use of S-19 vaccine for contagious abortion (Bang's disease). Its use spread rather slowly at first, possibly due to the farmers' instinctive caution, for so many remedies had already been tried, appeared promising, and then had failed. Later it was used widely and with confidence. There can be no doubt that, so far, it has made a most valuable contribution to checking losses from the dairy herd and so in raising milk production.

Figure 3 shows how quickly the sheep population decreased. Again, the loss fell chiefly on the arable areas. Grass sheep were still kept on those farms where they were unlikely to interfere with milk production. This was not a period of intensive activity in sheep husbandry, but work was proceeding on such things as newer types of sheep dips, possible trace element deficiencies, and the value of certain new crosses suitable for grass flocks.

The most common cross-bred ewe for that purpose, the Half Bred (Border Leicester x Cheviot), was in short supply and in great demand, and in consequence prices of young ewes were very high. The possibilities of alternatives, such as the Clun Forest and Kerry Hill breeds outside their native habitats or of crosses by a Dorset Horn or Border Leicester ram with a Welsh Mountain ewe, were being studied for such qualities as prolificacy, hardiness, and ability to produce fat lambs.

Pig and poultry farmers had to suffer the most severe feeding stuff cuts. The aim was to distribute any rationed feeding stuffs available for those classes of livestock so that the best herds and flocks might be preserved, but in reduced numbers. Allowances were given for pedigree pigs and for poultry in accredited flocks and these, though inadequate, were invaluable in assisting to maintain a nucleus of sound stock.

Feed rations were also made available to domestic poultry keepers on the basis of the number of personal ration books in the household. In all districts except the most highly populated centers of the large towns, this scheme was taken up readily and resulted in the production of much useful food from a modest allowance of balancer meal supplemented by household scraps.

The agricultural scientist and the adviser worked with enthusiasm in the knowledge that they had an important role in the national emergency. A pleasant reward of their work came through the realization that science was making a contribution toward higher production on most farms. Wartime powers had given the adviser a right of entry to every farm at a time when all but a few farmers were in a responsive mood. His influence then was quite far reaching. The more recent findings of research at such well-known stations as Rothamsted, the National Institute of Research in Dairying, and Long Ashton came to be applied in farm practice on many farms where science had formerly been regarded with suspicion.

Heavy demands were made for soil sampling, for analyses, for potato root eelworm and wireworm counts, or to determine the suitability of a soil for mole draining. The use of seed treatments for cereals to control bunt and leaf stripe diseases became a general practice, and varieties were selected with care to suit local conditions. Crops generally were better fertilized. Farm planning for maximum production of crops and stock involved advisers in a new type of work for which there had been little previous enquiry. By visits to individual farms, by group discussions, by farm walks, lectures, demonstrations, and the advisory leaflet, the adviser widened his sphere of influence.

He was learning too, for in cooperation with the research worker there were many opportunities for testing out alternative methods of reclaiming derelict land or refertilizing land that had been allowed to run down. This new work also threw up a number of interesting problems on land but newly under the plow, which would clearly demand solution if a high tillage area was to be maintained in postwar years.

## III. The Period 1946–1950

### 1. *Agricultural Policy*

It was perhaps natural that farmers should be rather nervous of the future at the end of World War II. Was there to be a repetition of 1921, now that the immediate emergency was over? They were quickly assured of the importance of a continuing high output from home farms and were reminded that the huge war expenditure had so reduced overseas investments as to create a situation very different from that in 1920. There was also the promise of legislation to guarantee prices of certain farm products in relation to costs.

The end of the war in fact brought little change in farming systems. There was still a need for the maximum production of bread and coarse grains, of potatoes, and of those other feeding stuffs and fodders which would make farms as self-sufficient as possible for livestock. The industry was told that there seemed little prospect of importing large consignments of feeding stuffs and that an expanding livestock production must be dependent much more than formerly on feeding stuffs grown at home. Production targets were set in 1947 for a four-year period, the aim being to attain in 1952–53 150 per cent of prewar production based on farm commodity values in the year 1946–47. Later this target was reduced to 147 per cent.

Another indication of the future pattern of agriculture became clearer with the introduction of the Agriculture Act, 1947. Its provisions, by comparison with a number of the earlier Acts, were somewhat revolutionary in character and so merit a reference here.

The Act had five parts: (1) Guaranteed Prices and Assured Markets; (2) Good Estate Management and Good Husbandry; (3) Agricultural Holdings; (4) Smallholdings; (5) Administrative and General.

Part 1 provided for the fixing of prices of the chief farm products at an annual review. At present these products include fat cattle, sheep and pigs, cow's milk, eggs in shell, wheat, barley, oats, rye, potatoes, and sugar beet, but the possibility of extending the list to cover other products was mentioned. The general argument in part 2 was to the effect that in return for guaranteed prices, the industry must show that it was efficient. Power was therefore taken to ensure that cases of bad estate management on the part of the owner or bad husbandry on the part of the operator were brought to light. If, after advice (possibly under definite directions for a period of supervision) no improvement was made, there was authority subject to appeal to dispossess an owner or terminate a tenancy. Parts 3 and 4 dealt respectively with the relationship between owners and tenants and the setting up of smallholdings by county councils, really an extension and modification of earlier legislation. Finally, part 5 dealt with the formation of county agricultural executive committees, an agricultural land commission, and agricultural land tribunals. It gave powers to the Minister to acquire land under special circumstances and generally to secure or maintain increased production.

A further important Act, the Agricultural Holdings Act, 1948, dealt chiefly with the relationship of landlord and tenant in such matters as tenancy agreements and compensation for disturbance and improvements.

An important change came with the setting up of the National Agricultural Advisory Service in October, 1946, for which authority had been given in an Act of 1944. County councils were still to retain their responsibilities for the running of farm institutes (farm schools), for other forms of vocational agricultural education for young people and for advice to domestic producers, but the new national service took over responsibility for advice to commercial producers. Officers who in 1939 had been in the agricultural education service of county councils or had held specialist advisory posts at universities were given a right of transfer to the new government service. Most elected to accept this option.

Eight provincial centers, each near a university or college, were set up to assist the field officers with their more difficult problems. The technical staff consisted of a provincial director and deputy, science specialists in soil chemistry, nutrition chemistry, entomology, plant pathology and bacteriology, and husbandry advisory officers in crops, grass, machinery, livestock, poultry, milk production, and horticulture. Later an appointment of an advisory aids officer was made at each center. The county technical staff consisted of a county agricultural officer, advisory officers in livestock, poultry, milk production, machinery, and horticulture, and district advisory officers, the latter on the basis of one for each 1,000 farms.

The complement is not yet full, but steadily a staff is being built up. The work of the county and district officers in particular is linked closely with that of the county agricultural executive committees, so continuing with little change the wartime arrangements.

Later another government advisory service, the Agricultural Land Service, was formed. The nucleus of its staff was obtained from those who as land commissioners had been the Ministry's officers in close contact with county committees and with the agricultural side of county councils' work in which the Ministry had an interest, for example, smallholdings. This new service is responsible for advice in estate management and fixed equipment and assists in implementing those provisions in the Agriculture Act, 1947, relating to the rights and obligations of landowners and tenants. Provincial land commissioners were appointed to the eight provinces referred to above, under each there are a number of land commissioners and in each county a committee land agent.

Here was a great change and indeed something in the nature of a large-scale experiment. The advisory services in husbandry and estate management were to be staffed solely by government servants, and, unlike other branches of the civil service, the staff was to carry out a large part of its work in close cooperation with county and district committees, serving in a voluntary capacity.

Another new line of policy was drawn in the decision to set up a national chain of eighteen experimental husbandry farms and eight experimental horticulture stations. These were to be chosen carefully to represent land on the chief soil types and subject to widely varying climatic conditions and were to act as substations to the existing research stations and to provide facilities for experiments by the advisory service. The farm and station directors would be members of the National Agricultural Advisory Service, and the Ministry would be advised on the experimental program by committees consisting of equal representation of the Agricultural Improvement Council, the Agricultural Research Council, and the National Agricultural Advisory Service with independent chairmen.

This organization, to advise on priorities and to coordinate experimental work generally, was deemed essential, for it was evident that very many requests for experimental facilities would be received. So far eight farms and three stations have been acquired, and preparations are now under way to start long-term investigations on such matters as the ley as a fertility builder, straw disposal, variety trials, the nutrition of fruit, vegetable, and glass-house crops, the treatment of flowering bulbs, varying levels of nutrition in rearing dairy heifers, cross-bred vigor in pigs, and poultry management.

### 2. *Recent Developments*

Experience during the emergency had shown that large tracts of the heaviest clay soils, formerly in permanent grass, were capable of high yields under arable crops, provided the land was well drained and that cultivations were timely and adequate. The introduction of the modern crawler tractor with its reserve of power had changed the outlook. Much of such land, plowed during the war, has continued under arable cultivation and, though not yielding quite so well as when plowed out of old grass or scrub, commonly produces crops quite up to the national average.

The work of producing and proving better varieties of the more common crops continued and indeed became more intensive. Experimental work had been curtailed through the demands of other essential wartime work, but now the National Agricultural Advisory Service through its field officers cooperated with the National Institute of Agricultural Botany in numerous trials of cereals and potatoes. The results of the first three-year trial period will be available in the autumn of 1951, and the information so far available indicates that these should prove of high value to farmers in selecting suitable varieties for local conditions.

The need to produce more protein directed attention to other arable crops that might be suitable for this purpose. It was thought that linseed, both for protein and oil, might be grown more extensively, but the gross returns per acre were not favorable enough to encourage farmers to grow this crop, and only a small acreage is now sown. The soybean was tried, but no variety was found reliable in this climate. Experimental work is in progress in the growing of oil seed crops such as rape (colza), sunflower, and poppies, but so far these crops are not in commercial production.

Beans and peas, the older and more common protein crops, continued to be grown on higher acreages, but yields were not too satisfactory, and rather than increase still further the acreages of these crops, many farmers turned elsewhere for sources of protein, for example, to silage from specially grown crops and leys or to kale.

The growing of grasses and clovers for seed production became an important feature in certain favored areas. Little was known of the technique for the successful production of seed of the more common grasses such as cocksfoot (orchard grass), timothy, and meadow fescue on a field scale, though the rye grasses and red clovers had been grown for seed for many years. The relative merits of row cultivation and a broadcast stand were examined in relation not only to seed production but also as to how the sward would fit in with the grazing economy of the farm. The use of fertilizers and the correct time to apply them were also under investigation.

Fertilizer practice changed in several directions. The recognition that phosphate fixation in the soil could reduce very considerably the amount of phosphate recovered through the crop exerted an influence toward the modern practice of applying it little and often in a crop rotation as opposed to larger applications less frequently. There was a turning toward standard mixtures of granular fertilizer, and a greater proportion was used through combine drills for cereal crops. Experiments had indicated that suitable placement could result in a saving on fertilizer. A given quantity combine drilled could give results comparable with those obtained from double that quantity broadcast. Experience also confirmed that an application of fertilizers in the potato rows before planting normally was more effective than a similar application given before ridging or after planting.

So many areas of the country had been short of lime that few questioned whether there was any risk of applying too much to a soil already well supplied or with only a small lime requirement. Recent research, however, had shown that there were dangers of overliming in inducing deficiences of other elements and so in affecting crop yields. Farmers in consequence became more reluctant to lime and fertilize until advised as to the need and the quantity to be applied. A short but quite startling example of the use now made of the advisory service is brought out by the following figures. In the middle 1930's about 3,000 soil samples were taken annually for analysis; in 1949 the figure was 171,000; in 1950 the number is expected to reach 200,000.

Several recent cases have been reported of troubles believed to be caused by a deficiency of a trace element, and it would seem that some of the unsatisfactory yields of crops and production from livestock may be due to this cause. Undue importance should not be given to possibilities of widespread improvement in this direction, but so far local detailed investigations have brought to light symptoms of cobalt, copper, boron, and manganese deficiences in well-defined areas hitherto unsuspected.

Grass, temporary and permanent, has come to be recognized as the country's most important crop. During the past few years there has been a new and growing appreciation of its value and a recognition that it can make a major contribution to production, if managed right. The use of more leafy strains of grasses and clovers for leys, the sowing of a proportion of special-purpose as well as general-purpose mixtures, and the infinite variations in management to attain differing results, are now widely accepted. Each can contribute to meet the livestock requirements of the individual farm. Better fertilizing for out-of-season and higher production is now a feature of the management of the more progressive farmers, and the utilization of grass at its most nutritious stage and with the minimum loss is being effected by strip grazing and by the conservation of seasonal surpluses as silage and good quality hay. Silage from grass, made in pit silos, with the use of modern mechanical aids, now provides an increasing amount of winter food for ruminant livestock. Dried grass production is also expanding. Though there is still much room for a wider use of better methods in a number of areas, progress in ways and means to make the most of our grass is very encouraging and seems likely to continue.

On the hill land, improvements of limited areas by plowing, fertilizing, and reseeding or by fertilizing alone have been encouraged through government assisted schemes. Here the management factor is of extreme importance. There is still some uncertainty as to whether improvements at high altitudes can be maintained even under the most carefully controlled conditions of stocking and how far these may influence the qualities of hardiness so essential in our hill sheep breeding flocks. There is a wide field for research here and in the associated problem of preventing the spread of bracken fern, which has been slowly creeping up many hillsides in recent years.

The declining interest in the breeding of draft horses can be judged from the fact that less than 5,000 mares were covered in 1948 by the 89 stallions of the 78 grant-aided societies—just under one third of the number served in 1939. The demand for heavy horses for work outside the farm has slackened appreciably, and there seems no prospect of a revival of interest.

The reverse is certainly true of cattle, particularly dairy cattle. Milk production has been stepped up so quickly that the target output figure for 1952–53 has already been reached through the combined effects of a larger cow population and a higher average yield per cow. It is perhaps rather too early to attempt to assess how much of the improvement is due to breeding, though the substitution of dairy in place of general-purpose breeds in a number of herds may have had some influence. Undoubtedly a major part of the improvement has come through better management and feeding.

The impetus to upgrade dairy herds was reflected in the demand for bull licenses of three sorts, dairy, beef, or general purpose. This was met in new regulations introduced in 1945, which laid down that for a dairy license the bull's dam and sire's dam must have given not less than 6,000 lb. with their first lactation, 7,000 with their second and 8,000 with their third and subsequent lactations, each of not more than one year. By

1949–50 almost 40 per cent of the bulls approved were eligible for dairy licenses.

Meantime the demand for artificial insemination had grown until, in 1950, there were 29 centers and 75 subcenters of which 21 and 54 respectively were administered by the Milk Marketing Board. From small beginnings in 1942, interest had grown so rapidly that over 600 bulls are now in use, and it is estimated some 28 per cent of all cows bred from in 1950 will have been inseminated. In 1947 under a Ministry scheme, free services by "color marking" beef bulls (Hereford, Aberdeen Angus, and Galloway) were offered by various artificial insemination centers to encourage herd owners to put their low-yielding cows to good beef bulls and so obtain better calves for rearing for beef. The scheme during a three-year period has been a marked success and is to be continued on the basis that herd owners will pay 12/6d (approximately $1.75) per service by a beef bull, half the full fee charged for semen from a dairy bull.

There has also been a noticeable increase in the number of calves reared and improvement in the method of rearing as the result of a Calf Subsidy Scheme. This provision has undoubtedly had a considerable effect in reducing the number of calves slaughtered soon after birth for veal, and in consequence more have been available for rearing for beef.

Under livestock improvement regulations licensing of boars on much the same lines as with bulls came into force in 1946. During 1949–50 a total of 9,113 were licensed, the majority being of the Large White, the Wessex Saddleback, and the Essex breeds.

Another recent development has arisen from the Hill Ram (Control) Order made in 1942 and subsequent regulations. The aim is to confine the use of rams in hill flocks to those suitable for this purpose. The responsibility for the administration of the regulations has been delegated to County Agricultural Executive Committees, who may have to deal with possibly 50,000 rams. In passing, it is interesting to note (Fig. 3) that the sheep population is again reaching the numbers of 1946. The winter of 1946–47, with its severe and prolonged storms, caused a very high mortality in hill flocks.

## IV. Future Trends

### 1. *Technical Advances*

Further advances seem reasonably certain in a number of directions. The plant breeder will continue to strive for the production of new varieties of better quality, more resistant to pest and disease attack. In cereals, desirable features include early maturity for the later districts, strength of straw for the more fertile soils and where good responses are possible from liberal fertilizer treatment, and quality of grain in barley for malting. In the production of new types of herbiage plants, leafiness, period of maximum growth, and recovery power after defoliation are points of special importance in the choice of species for short-term leys.

Promising progress has already been made in the breeding of new potato varieties immune to blight, a serious disease in moist and warm summers. The aim is now to combine the capacity to give good yields of high quality tubers with that immunity.

Rapid advances have been made in recent years in methods of weed control, and change after change in practice has been made as first one and then another treatment proved more effective. The use of the growth-regulating substances is extending each year, and new products are continuously on test under the wide variety of climatic conditions common in this relatively small country. The need for materials of greater selectivity, particularly for weed control in such crops as peas and lucerne, is recognized, and interesting developments lie ahead both in that direction and in the improvement of pre-emergence sprays for use on row crops expensive to weed by hand. Fortunately, there is no disposition among farmers to regard chemical weed control as an alternative to ''clean'' farming.

The field is still wide for the development of labor-saving machines and equipment, despite the progress made in farm mechanization during the war years. Here reference is made to two examples of possible advances. More than 10 per cent of the sugar beet crop is harvested mechanically, and the area so harvested is increasing rapidly each year. It is only recently that moderately priced toppers and lifters have been adapted to deal with this crop on our varied soils, and the performance of a number of harvesters is now equal to that of good hand labor. Future developments may well lie in the better harvesting of the tops—free from soil and so suitable for feeding—the improvement in equipment to lift and clean the roots, and possibly the eventual production of one harvester suitable for a variety of crops such as sugar beet, potatoes, fodder beet, and other fodder roots.

With the development of new techniques in grassland management, there seems a promising field for further study in the adaptation and use of electric and other easily movable fences for strip grazing and the production of moderately priced and efficient forage harvesters to assist the smaller farmer in conserving grass and other green crops. Grass has assumed a new importance and is now recognized as one of our more important crops. Considerable initiative is likely to be shown in investigating the best and most economical means of grazing or conserving it.

A few years ago few thought that good beef could be a by-product of the dairy industry. Now that view is generally accepted. Improved methods of disease control have reduced herd losses and it is now unnecessary to serve all the cows with a dairy bull to obtain sufficient herd replacements. The poorer cows can be served by a good color-marking beef bull and so provide a supply of calves suitable for rearing for beef.

In the wide field of disease control, interesting developments include the introduction of a revised attested scheme for the elimination of bovine tuberculosis and recent work on mastitis and calf-hood scours, which point to possibilities of controlling the losses from these rather common ailments.

Brief reference might also be made to other possible advances of a more speculative character such as the practical application of egg implantation, the promotion of quicker growth and earlier maturity in fattening animals through the use of certain food accessories, and the use of new types of fertilizers. Further work however, is still necessary to show whether they are likely to make an important contribution to agricultural production.

The broader interest in the importance of home agriculture created during the war has led to a reexamination of the need for research and the means of transmitting its findings to the farmer. Two new fields of research are being developed through the provision of a Vegetable Research Station and an Institute of Animal Pathology, and, as mentioned earlier, the link with farm practice has been strengthened through the establishment of a National Agricultural Advisory Service and its experimental husbandry farms and horticultural stations.

The number of farm institutes has also increased under the administration of local education authorities. The majority of the students in the immediate postwar years were ex-service men and women on vocational training courses, but now most are country-born young men and women in their late teens, who had decided before entering the institutes to take up some type of agricultural work.

## 2. *Farm Buildings and Land Use*

Many of our farm buildings are over 100 years old and, though built substantially, now show the need for major repairs. They were erected at a time when labor and materials were relatively cheap and when there seemed little prospect of drastic changes in practice or in the application of mechanical power to farming. High building costs and the advantages of adaptable buildings are leading to a simplification of design and to a decision to build for a life of 25 years or so. Adaptations of old buildings in sound structural condition are still being made to provide cover for such purposes as grain drying, machinery storage, and cattle yards, and, as electrical power becomes available in more rural districts, it is being introduced for various barn operations. Yet there are many farms where a new and simplified layout proves to be less costly than substantial alterations to existing buildings, and sets of new farm buildings are appearing here and there, particularly in the traditional arable areas.

Agriculture in England and Wales has developed slowly through the centuries from a means of subsistence to an industry, and that development has been accompanied by changes in systems of land tenure. Recent tendencies have been toward an increase in the number of owner-operators and for farm units to become smaller through a variety of causes such as inheritance, the sale of estates to pay death duties, and the development of intensive cultivation on small areas. The average agricultural holding is well under 100 acres, and in many counties over 60 per cent of all operators now farm between 1 and 50 acres. Further subdivision, however, seems improbable, indeed, there is a prospect of some amalgamation of holdings, particularly in certain industrial and poor-land areas. A number of owner-operators of small and uneconomic units, when judged by normal standards, are likely to remain, men with independent ideas who maintain that, by long hours of hard work, they can compete with their better organized and equipped neighbors farming larger holdings. The evidence, however, points to the gradual decrease in the number of individual holdings in spite of the real land hunger which has become apparent. Indeed, one problem of the future is clearly how new blood can be introduced into farming, assuming that tenants continue to enjoy the large measure of security provided by law; for nothing short of bad husbandry can now be brought forward as a reason for terminating a farm tenancy.

Much more attention is certain to be given in the future to farm management studies both in teaching and in advisory work. In the past, new practices have sometimes been introduced without a true appreciation of their effect on the organization of farm labor or on the economy of the farm as a whole. Recently, however, the adviser has received an increasing number of problems on farm management, and it is clear that the National Agricultural Advisory Service will be required to give careful thought to the training of its staff to meet this new demand. In this connection, it is of interest to note that arrangements are being made for contacts and a small interchange of staff with those engaged on farm efficiency studies in America. It is believed this cooperation will be mutually helpful and will give guidance for the future training of our younger officers in this important aspect of their work.

What of the tasks ahead? There is little hope of expanding the agricultural area, though the improvement of the better marginal land areas, as contemplated under the Livestock Rearing Act, 1951, could assist in increasing the production of store cattle and sheep. Even including such land, however, the area of land per head of the population is but a fraction of an acre, and agriculture is merely one of many industries competing for labor.

There is a clear call to strive for high output both per acre and per man. In output per acre England compares unfavorably with certain continental countries such as Belgium, Denmark, and Holland, but it greatly exceeds these countries in output per man, though it still is far short of the man-output of America. While maintaining and indeed striving to increase production per acre, England must examine the possibilities of increasing output per man, a side of production somewhat overlooked during the all-out effort for maximum production under wartime conditions.

Whatever the future may hold, there will still be wide variations in farming systems due to differences of soil, climate, or size of holding. Rainfall alone can vary from 22 to over 100 in. per annum within the boundaries of England and Wales and so plays a predominant part in determining the most appropriate system of farming for a particular district. There will always be a place in the country's farming for the expression of initiative. The farmer with an eye for a beast, the hill sheep enthusiast, and the born applied mechanic will each do their best work if allowed to follow their natural bents. Through the centuries such men have been the pioneers in agriculture and the mainsprings of true progress.

# The Adaptability and Breeding of Suitable Grasses for the Southeastern States *

GLENN W. BURTON

*U.S. Department of Agriculture, Tifton, Georgia*

CONTENTS

| | Page |
|---|---|
| I. Introduction | 197 |
| II. The Problem of Evaluating Grasses | 201 |
| III. The Grasses | 205 |
| 1. Bahia Grass | 206 |
| 2. Bermuda Grass | 209 |
| 3. Carpet Grass | 213 |
| 4. Centipede Grass | 214 |
| 5. Dallis Grass | 216 |
| 6. Italian Ryegrass | 218 |
| 7. Johnson Grass | 220 |
| 8. Kentucky Bluegrass | 222 |
| 9. Napier Grass | 224 |
| 10. Orchard Grass | 226 |
| 11. Pangola Grass | 228 |
| 12. Pearl Millet | 229 |
| 13. St. Augustine Grass | 232 |
| 14. Sudan Grass | 233 |
| 15. Tall Fescue | 236 |
| 16. Vasey Grass | 237 |
| 17. Zoysia Grass | 239 |
| References | 240 |

## I. INTRODUCTION

Fitting crop plants to the environment is one of the major responsibilities of the agronomist. Whether he is concerned with the actual testing of crop plants under a given set of environmental conditions, or whether he is occupied with the many problems associated with altering the plant or the environment, it matters little. In the end there is only one goal, greater and more efficient production. Even those concerned with the saving of the soil are charged with this responsibility in order that there may be greater production in the future.

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* Cooperative investigations at Tifton, Georgia, of the Division of Forage Crops and Diseases, Bureau of Plant Industry, Soils and Agricultural Engineering, Agricultural Research Administration, U.S. Department of Agriculture, The Georgia Coastal Plain Experiment Station, and the Georgia Experiment Station. The writer expresses sincere thanks to those workers who granted permission to use their unpublished data.

The greatest production results when the plant and the environment are in perfect harmony. Nature has created this harmonious balance over a period of thousands of years, developing what the ecologist calls a climax-formation. It is often defined as the highest type of vegetation that a climate will support. Although the greatest emphasis is rightly placed upon the influence of the climate, such factors as soil fertility, soil texture, and soil drainage influence the type of vegetation that an area will support.

As the agronomist assumes the task of fitting crop plants to any environment, he must first take inventory of the features of the environment and the native vegetation that it will support. Such an inventory of the southeastern United States, frequently referred to as the humid South (which in this paper will include southeastern Oklahoma, Arkansas, Tennessee, North Carolina, and the area south to the Gulf), reveals some interesting facts. It is a region of heavy precipitation averaging from 45 to 60 in. of rainfall annually. Although the fall tends to be somewhat drier than the other seasons, the rainfall is reasonably well distributed throughout the year. The humidity is high during most of the year, making conditions ideal for the development of plant disease. Summer temperatures average 80 degrees and more, and winter temperatures range from 40 degrees in the north to more than 65 in the extreme tip of peninsular Florida. The growing season (number of frost-free days) exceeds seven months for more than half of this area.

The soils of the humid South are classified largely as red and yellow soils. They are lower in alkalis, alkali earths, and silicates and higher in iron and aluminum than the soils farther north. They may be further subdivided on the basis of their parent material. In the Piedmont and mountains the soils formed from materials laid down in the Paleozioc Age or before are heavier, more mature, and generally more fertile than those in the Coastal Plain. There the sandy materials pushed up mainly in the Tertiary Age have not been subjected to soil forming processes long enough to develop mature soils. Some of these soils have not developed good horizons and are so sandy that they hold moisture and plant food very poorly. Analyses of these soils in their virgin state usually reveal that they are very low in organic matter, bases, and the elements required for plant growth. Notable exceptions are the alluvial soils and the prairie soils that have developed in limited areas, such as the "Black Belt" of Alabama and Mississippi. Soil erosion resulting from faulty soil management has taken a heavy toll in much of this area that man has put under the plow. Practically all these soils as the agronomist finds them today are too poor to support the growth that the climate will permit.

Weaver and Clements (1929) consider the humid South to be a part of the deciduous forest climax that blankets the eastern half of the United States. The great pine belt that characterizes most of the Coastal Plain in this region is thought by many to be essentially a fire subclimax. The fact that deciduous hardwoods occur on the islands of heavy soil in this belt suggests, however, that the droughty infertile nature of the immature Coastal Plain soils may be an even more important factor limiting the growth of deciduous trees. Men, like William Bartram (Van Doren, 1928), who traveled this area before the American Revolution and who recorded what they saw, give an excellent picture of the flora at that time. They described the region as a timberland with a lush growth of grass wherever the stands were open enough to permit its growth. They observed large patches of maiden cane growing along the streams and in the large swamps that they encountered. Their description of the flatwoods of the Coastal Plain with its palmettos and shrubs indicates that the type of vegetation there has changed little since their day.

Following the standard pattern, the first white farmers settled along the rivers and began to clear small areas in which to grow cotton and corn. Before the coming of the railroads those who moved farther into the interior grazed the grassy savannahs with sheep and cattle. With the coming of the railroads came huge sawmills that soon stripped the land of most of its good timber. Once the trees were gone, farmers receiving grants or buying the land (often for less than a dollar an acre) began to move in and farm the ridges, dodging the stumps with their oxen and crude farm implements. Cotton and corn furnished the main source of income, and cattle grazed free range on the cutover land that was left. Those who owned the cattle that grazed the native grasses soon discovered that generally they made poor quality feed. Even with annual burning to remove the unpalatable dead grass, the cattle made good gains only during the spring months. During the summer they barely maintained their weight though standing knee deep in grass, and during the fall and winter they lost most of the weight that they had gained in the spring. From 15 to 30 acres were required to carry one animal around the calendar. The calf crop was less than 50 per cent. The returns were low but so were the costs, and as long as there was enough free range, those who owned the cattle made money.

A few plantation owners, like Thomas Spalding of Sapaloe Island, recognized the poor quality of the native wire grass before 1800 and began introducing and planting pasture plants from other parts of the world. Although they did not bear the title, they were really the agronomists of their day. In his diary Spalding made the following entry: "Bermuda grass was brought to Savannah in 1751 by Governor Henry Ellis. If ever this becomes a grazing country, it must be through the instrumentality of this grass." Dallis grass, introduced into the South from South America about the middle of the last century, bears the name of A. T. Dallis of LaGrange, Georgia, who grew it extensively. This search for new grasses and legumes that will be better suited to the humid South is still under way.

It is doubtful if grasses will be found that will be better adapted to the virgin soil and climate of the South than the native aristidas, andropogons, panicums, etc. They are being replaced because they are not well suited to the uses that man now has for grass. Obviously, the first test of any new grass, be it a new species or a variety, is its ability to survive. Strange as it may seem, winter temperatures have limited materially the distribution and usefulness of a number of grass introductions. Napier grass, Rhodes grass, Pangola grass, and Bahia grass are notable examples of promising species that will be restricted to the southern part of this region until more cold-tolerant strains are found. In parts of the Coastal Plain the water-holding capacity of the deep sandy soil is so low that in spite of well-distributed rainfall, only drought-resistant species with extensive root systems show much promise.

Many of the introduced grasses and legumes that are more palatable and more nutritious than the native species will not grow on most southern soils until the soil fertility has been raised. Burton and Mathews * found that *Crotalaria lanceolota* E. Mey. (one of the poor land legumes) grew less than 3 in. high and barely survived on newly cleared virgin Tifton soil. Given 600 lb. per acre of 4-8-6 fertilizer it grew more than 2 ft. high. Most of the grasses being used in the South for improved pastures made less growth than the best native species where fertilizer was withheld. White Dutch clover, big trefoil, and many of the other legumes could not be established on virgin Coastal Plain soil until lime and fertilizer were applied. Hodges and Kirk * working at the Range Cattle Experiment Station at Ona, Florida, have data to indicate that the beef gains from unfertilized carpet grass (an improved species that can be introduced without fertilization) may be no better than those from the unfertilized native range. Many of the flatwoods and lowland soils must be drained before satisfactory growth of the more common introduced pasture plants can be had. Another possible solution to this problem lies in the discovery of grasses like Vasey grass (*Paspalum urvillei* Steud.) that are capable of growing on poorly drained soils.

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* This and subsequent references in which the author's name is followed by an asterisk relate to unpublished data obtained from the author named.

As the agronomist searches for better grasses suitable to this large region, he dare not disregard the biological environment. Plant disease, favored by high humidity and optimum temperatures, reduces the production of most of the grasses that have been introduced into the South. Disease-resistant strains of Napier grass and Sudan grass, to mention only two, have outyielded by substantial margins the old susceptible strains. If measured in terms of total digestible nutrients, the differences would probably be even greater. The role of insects in reducing the yields of both seed and forage and in spreading diseases, such as ergot in southern grasses, has been recognized. Thus, the breeding of grassland plants for resistance to disease and insect damage promises to be a fruitful enterprise.

Since the products of the grass testing and breeding programs will, for the most part, be utilized by livestock, the requirements of livestock must always be kept paramount in the mind of the agronomist. The need for a uniform year-round supply of feed places emphasis on selecting pasture types which will extend the grazing period and make for more uniform seasonal production. Grasses to supply winter feed and bridge gaps in the seasonal production of permanent pastures must be found. Although maximum total production is important, maximum production of dry matter must not be confused with the real objective; namely, maximum production of total digestible nutrients. Quality and balance of digestible nutrients also demand attention. Since animal production and performance are dependent upon food intake, it is important that new strains of grass be highly palatable as well as nutritious. Although the palatability and nutritive value of grass can be favorably influenced by careful management, such management may often be costly and sometimes impracticable. The discovery, therefore, of grasses that will persist and perform well under favorable management and will be eaten when mature is highly desirable.

## II. The Problem of Evaluating Grasses

Accurately evaluating grasses for pastures is a difficult and an expensive operation. Most agronomists begin the task by planting the grasses in rows or plots in pure stand. There they are allowed to grow undisturbed, and if they fail to survive the first twelve months, they are usually written off as having no value. This conclusion may not be correct. Dallis grass, recognized as one of the best pasture grasses in the South, makes a poor showing in such a planting. Plantings of Dallis grass at Tifton, Georgia, that were never grazed or mowed, have made good growth during the first part of the summer but have died out by fall. The combined effect of the foliage diseases that build up in the accumulated mass of leaves and the heading process was probably responsible for these results. Tall fescue, another promising grass in the South, makes a poor record in such a planting if it is not well fertilized. Grasses, such as Vasey grass, that make an excellent showing in the nursery test, will soon disappear under close grazing in a pasture. It would seem, therefore, that the initial test of potential pasture grasses should include two different levels of fertility and at least two systems of management. Mowing to simulate grazing may be substituted for grazing, although the need for additional information may justify the use of cattle to keep the grasses grazed down.

The means by which new grasses can be propagated should be given consideration early in their evaluation. Seed production usually is set as a prime requirement for new grasses. This need not be, however, particularly if they are stoloniferous and spread rapidly. Pangola grass and Coastal Bermuda are examples of two seedless grasses that are being planted by vegetative means on thousands of acres in the South. Many farmers have found that they can establish these grasses from sprigs or mowings taken from their own nurseries for less than the cost of establishing other pasture grasses from seed.

The question of the control of new grasses cannot be overlooked. New grasses that are well adapted and aggressive should be carefully checked on this point before they are released, particularly if they produce seed. Centipede grass seeds have been carried from one pasture to another in cows droppings, and the plants that grew from such seeds have completely crowded out Bermuda grass. As a result the productivity of the pasture dropped from 140 to 30 lb. of beef per acre per year. Burton and Andrews (1948) have shown that cattle still passed a few viable seeds of most of the southern pasture grasses ten days after they were fed. The role that cattle play in scattering grasses from field to field and from farm to farm is apparent.

It is not enough to know that a grass will survive and grow, that it can be propagated economically, and that it will not be a serious pest. Some provision must be made to discover if it will be eaten by the class of livestock that will be its ultimate consumer. Plants like nutgrass would pass a part of the nursery test very well but would be refused by cattle. The "Cow Cafeteria" has been used by many agronomists as a means of ascertaining the relative palatability of the grasses in question. These cafeterias usually consist of a group of plots (single or replicated) of a number of different species with several checks included. Cattle are given free access to the plots, and the time spent on each plot or the amount of forage removed by the animals furnishes an index of the relative palatability of each species. This has proved to be a useful technique, particularly in determining the relative palatability of different strains of a single species (Burton and Southwell, 1943). The limitations of the method should always be considered by those who would use it. Fertilization effects the growth and palatability of pasture plants. Burton and Mathews (1949) found that cattle located and grazed with much greater than average intensity 128 randomized 6x24-ft. plots that had received lime in a reseeding study located on a very acid Leon soil. These animals evidently craved calcium more than phosphorus, since they actually grazed the plots receiving lime closer than those receiving 100 lb. per acre of $P_2O_5$ from superphosphate. Nitrogen usually has an even more pronounced effect upon the palatability of a grass. ''Cafeterias'' are usually fertilized uniformly, but the rates and fertilizer ratios used are probably not optimum for all grasses and may affect the resnlts. Rogler (1944) has shown that maturity, grazing intensity, recovery rate, drought resistance, associated species in a mixture, previous feed, kind of stock, and individual differences in animals also affect palatability. He presented evidence to substantiate his conclusion that taste as well as the mechanical condition of the plant influenced its palatability.

Measuring the nutritive value of a grass poses even greater problems. The nutritive value of any forage plant is greatly influenced by the stage of growth at which it is harvested and the environmental conditions under which it grew. Unfertilized common Bermuda grass cut after it has matured seed will analyze 6 to 7 per cent protein. Grass from the same plots cut frequently, so that most of the sample is leaves, will contain twice as much protein. At Tifton, Georgia, it has been possible to double the protein content of Bermuda grass in almost any stage of growth by heavy applications of nitrogenous fertilizers. It is evident, therefore, that chemical analyses do not supply a good comparative picture of the nutritive value of a group of grasses unless they are grown under similar conditions and sampled at approximately the same stage of development. Ritchey and Henley (1936) grazed steers in uniformly fertilized pastures of carpet grass, Bermuda grass, centipede grass, common Bahia grass, and a mixture of grasses for a five-year period. Yields of forage, taken from enclosures at 28-day intervals, were also obtained. During the period of their test they found that the ratio of pounds of dry clippings to pounds of beef gain was about 11 to 1 and that it was essentially the same for all grasses except centipede grass, which was less until sampled by plucking. Then it became similar to the other grasses. These results suggested that there was little difference in the nutritive value of these grasses. Stephens (1942) working with an older and a purer stand of centipede grass found that cattle made poor gains on it. During a comparable three-year period, when the fertilization was similar, centipede grass produced an average of 31.2 lb. of beef gain per acre as compared with 140.3 lb. of beef gain from common Bermuda grass. Dividing the number of pounds of green clippings taken at 28-day intervals by the pounds of gain reveals that the ratio of green clippings to beef gain was 107 to 1 for centipede grass and 54 to 1 for common Bermuda grass. Over a four-year period (1945 to 1948) Stephens and Southwell * compared adjacent uniformly fertilized, six-acre pastures of two strains of Bahia grass grown in pure stand and stocked at the same rate. During this period, Pensacola Bahia produced 215 lb. of gain per acre per year as compared with 112 lb. of gain per acre per year from Paraguay Bahia. Clippings taken from cages at 28-day intervals showed the average annual dry matter production to be 3,040 lb. per acre on Pensacola Bahia and 2,795 lb. per acre on Paraguay Bahia. The ratio of dry clippings (taken at 28-day intervals) to beef gains during the course of this study was 14 to 1 for Pensacola Bahia and 25 to 1 for Paraguay Bahia. Burton and Boggess * clipped replicated plots of these two strains at two-week intervals during 1943 and subjected the clippings to chemical analyses. The average analyses shown in Table I indicate that Pensacola Bahia should have been slightly better than Paraguay Bahia in nutritive value. These data, together with the dry matter yields, could hardly explain, however, the striking differences in the gains that were obtained from the pastures of these grasses. Palatability trials indicated that the Pensacola Bahia was more palatable than the Paraguay strain and differences in the utilization of the two grasses in the pastures indicated that palatability differences were influencing the results.

TABLE I

Average Chemical Composition of Clippings Taken at Two-Week Intervals from Replicated Plots of Pensacola and Paraguay Bahia Grass during the Entire Growing Season in 1943

| Bahia Grass Strain | Percentage Composition on a Dry Basis | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Crude protein | Crude fiber | Cellulose | Lignin | Ether extract | Ash | Calcium | Phosphorus |
| Pensacola | 10.15 | 33.95 | 35.43 | 8.82 | 2.17 | 6.32 | 0.26 | 0.22 |
| Paraguay | 9.46 | 34.18 | 35.70 | 9.65 | 1.97 | 5.45 | 0.23 | 0.18 |

Stephens, Southwell, and Burton * in a grazing study designed to discover the amount of nitrogen that might economically be used on Coastal Bermuda for beef production obtained gains of 265, 323, 500, and 659 lb. of beef per acre from 20, 70, 120, and 220 lb. of nitrogen respectively for the period May 3 to September 20, 1950. The daily gains of the steers on these pastures were about 1.35 lb. and were not influenced by nitrogen level. Approximately 26 lb. of green matter were required per pound of gain regardless of the amount of nitrogen used. Hay production studies with this grass (Burton *) reveal that the grass receiving 220 lb. of nitrogen should have contained over a third more protein than the grass receiving only 20 lb. of nitrogen. The results suggest, therefore, that the protein needs of the animals were met by the lowest rate of nitrogen and that additional increments had no effect on the nutritive value of the grass. If these results can be repeated over a period of years, it should be possible to convert the clipping results from small plot fertilizer studies on Coastal Bermuda (perhaps other grasses also) into pounds of beef gain, thus avoiding the high cost of running actual grazing experiments.

The agronomist must always consider the compatability of new grasses when grown in association with other grasses and legumes. This raises the problem of the choice of the legume to be associated with the grass and the fertilization and management to be given to both. As grassland agriculture moves into the South, there will be an increased demand for grasses that fit well into sod-cultivated crop rotations. The search for such species is already under way.

It is evident from the discussion above that the agronomist can obtain considerable information concerning the usefulness of a grass from plot tests. Once the nutritive value of a species or a particular mixture has been established in terms of livestock products, he may be able to convert his results into information of value to the farmer without using the time and money required to test them with animals in pastures. Until more information concerning the evaluation of grasses is available, however, it would seem that new grasses must be grazed in pure stand by the class of livestock that will be their ultimate consumer, if their palatability and nutritive value are to be ascertained with any degree of accuracy. The need in this work for close cooperation between agronomists and livestock specialists is apparent.

## III. The Grasses

For the purpose of this discussion each grass will be treated in alphabetical order under its common name. In keeping with the objective of the *Advances,* an effort will be made to bring up-to-date the information in the field. The reader must realize that the field in question is so new that information on many of the simple questions is lacking or only fragmentary. Considerable unpublished information will be included in an effort to make the treatment of the subject more nearly complete. This procedure entails the calculated risk of drawing conclusions that may not always stand the test of further investigation. It is hoped that the benefit to be derived from making such information available now will more than offset the loss that may result should some errors be made.

### 1. *Bahia Grass*

*a. Origin and History.* Bahia grass, *Paspalum notatum* Flügge, probably originated in South America where it is one of the major pasture species. One of the first introductions by the U.S. Department of Agriculture was made from Brazil in 1914. It may have arrived much earlier in ship ballast, however, since it has been found growing wild around several southern seaports.

*b. Description.* Burton (1946) has described six distinct types, only two of which have assumed, or seem likely to assume, much importance. Both strains are deep-rooted perennials that spread slowly by short, stout stolons. Most of the leaves are borne in dense tufts near the base of the culms. Common Bahia has broader, tenderer leaves than Pensacola Bahia, making it more palatable during all stages of growth. The culms of Pensacola Bahia are taller (18 to 36 in.) than those of common Bahia (8 to 18 in.) but both grasses seed profusely throughout the summer. Burton (1943) has shown that early spring burning of the dead top growth and spring applications of nitrogen fertilizer increase seed yields several fold. The seeds of both grasses are enclosed in waxy glumes and will not germinate readily unless scarified with sulfuric acid (Burton, 1940a). Pensacola Bahia seed require much less scarification than common Bahia seed and are usually planted without scarification. Two to three years are required to establish common Bahia from unscarified seed.

*c. Adaptation and Use.* Common Bahia has winterkilled badly at Tifton, Georgia, during severe winters which means that it can be used safely only in Florida and the lower Coastal Plain. Pensacola Bahia has more frost and cold resistance and can be planted throughout the Coastal Plain. Neither grass is exacting so far as its soil requirements are concerned. They will thrive on wet or dry soils and will grow on soils that are too poor to support most of the grasses considered here. Ergot, *Claviceps paspali*, eyespot, *Helminthosporium* sp., and *Rhizoctonia* sp. have been observed on these grasses, but the damage caused by these diseases has not been extensive.

Both grasses are being planted in Florida for summer pasture. Pensacola Bahia starts growing early in the spring and often continues to grow after light frosts have killed common Bahia. When compared in clipped plots (Burton *), Pensacola Bahia has produced considerably more dry matter than common Bahia, more than twice as much in some years. Grazing results at Ona, in south Florida, (Hodges and Kirk *) indicate that Pensacola Bahia will produce 50 per cent more beef than common Bahia when grown in pure stand. Others have expressed the opinion that there is little difference in the beef gains to be had from these two grasses when grown on the heavier soils of North Florida. Careful grazing management is important with these grasses (particularly Pensacola Bahia) in order to keep them in a palatable condition. Some mowing will be necessary under most circumstances to achieve this end. Crimson clover and white Dutch clover have been successfully grown with Bahia grass on land that is adapted to them. Adequate fertilization and management are essential, since the dense sod formed by Bahia grass may prevent successful legume establishment. The Bahia grasses are not good hay grasses, although some farmers have made hay from them. Since they will make a dense turf on very poor soils, they offer promise for sodding airfields, road shoulders, and similar areas where a heavy duty turf is required. They produce too many seed heads and are too hard to mow to make them suitable for use on lawns.

The Bahia grasses appear to be particularly well suited for pasture use where the soils are poor and where good fertilization and maintenance programs are not likely to be continued. Excellent corn has been produced on land that had been in Bahia grass for six years, suggesting that it should be useful in sod-cultivated crop rotations.

There is considerable grazing evidence to indicate that the Bahia grasses are not as nutritious as Coastal Bermuda grass where the latter can be grown. Several pasture specialists have expressed the opinion that they are also inferior to Dallis grass. They are so well adapted and so aggressive, however, that they have crowded out tall fescue, Dallis grass, Bermuda grass, and carpet grass (except on low, wet soils). The Bahias seed over a period of about five months and, unless they are mowed frequently, viable seeds can be found throughout the summer in the droppings of the animals grazing them. Actual farm experience has demonstrated that Bahia grass will soon be found all over the farm as a result of the animals spreading it in their droppings. The seeds will remain viable in the soil for at least three years and, once Bahia grass becomes established on a farm, there will be enough plants in fence rows, etc. soon to reseed an area. It seems quite likely, therefore, that once the Bahias become well established on a farm, it will be difficult to maintain permanent pastures of other less aggressive grasses that may be superior.

*d. Breeding.* Common Bahia grass, a tetraploid, ($2n = 40$) is believed to reproduce almost entirely by apomixis (Burton, 1948a). Since apomixis may be defined as vegetative propagation through the seed, it is apparent that every seedling plant will have the same genetic makeup and the same characteristics as its female parent. The lack of variation in self- or cross-pollinated progenies prevents improvement of common Bahia by selection. So complete is apomixis in common Bahia that attempts to produce hybrids usually have given rise to seeds that grew into plants exactly like the female parent. The few hybrids that have been made have possessed the unreduced chromosome complement of the female parent and the reduced complement of the male parent. Most of these hybrids have produced seed (when pollinated with good pollen) that has given rise to nonsegregating apomictic progenies. One such hybrid having Pensacola Bahia as its female parent has shown more frost resistance than common Bahia and has outyielded it by a substantial margin. When grown within pollinating range of common or Pensacola Bahia, it has set good seed. When isolated from such pollen, it has been completely sterile, a characteristic that should keep it from spreading on farms where no other Bahia grass is now growing. Since this hybrid (a triploid) breeds true by apomixis and is superior to common Bahia, it is being increased and may ultimately find a place on the farm. It is evident that apomixis, when complete, greatly restricts the activities of the grass breeder. Its presence as the mode of reproduction in a superior individual does insure, however, that it will breed true, a very desirable condition once such plants are found.

The most promising approach to the improvement of common Bahia grass would seem to be the screening of introductions from South America. Most of the introductions of common Bahia have been identical in their appearance, however. One notable exception carried the P.I. number 148966 and was introduced from Argentina in 1944. Although this introduction looked much like common Bahia, it proved to be more frost resistant and has been completely immune to *Helminthosporium sativum* at Tifton, Georgia. In well-established clipped plots, it has outyielded common Bahia by more than 50 per cent. Preliminary investigations (Burton *) reveal that this introduction reproduces only by apomixis, meaning that it will breed true. It has been named Argentina Bahia and is being increased for distribution.

Pensacola Bahia, a diploid ($2n = 20$), appears to be entirely sexual in its reproduction (Burton *). Studies at Tifton, Georgia, reveal that it is highly variable in plant type, floret and anther color, leafiness, seed production, seed shattering, and forage yield. Superior clones have failed to set much seed when grown in isolation and have not bred true.

A study of the fertility relationships in 44 clones revealed that 80 per cent of them set less than 10 per cent of seed when selfed, indicating that they were highly self-sterile. When cross-pollinated, 80 to 90 per cent of their florets set seed. This self-sterility has been used to facilitate the evaluation of the general combining ability of clones in polycrosses, leading to the development of superior commercial hybrids (Burton, 1948b). One such hybrid, produced by planting vegetatively alternate rows of the two parent clones and harvesting all the open-pollinated seed produced in such a seed block year after year, has yielded 25 to 30 per cent more forage than ordinary Pensacola Bahia and has been superior in leafiness. Eighty pounds of seed of this hybrid were produced in 1950 for grazing studies.

### *2. Bermuda Grass*

*a. Origin and History.* Bermuda grass, *Cynodon dactylon* (L.) Pers., is found throughout the tropical and subtropical parts of the world. Most early writers have expressed the opinion that it originated in India, but the greater diversity of types shown by *Cynodon* introductions from Africa suggest that Africa may have been its primary center of origin. When or how it reached the United States is not known. Thomas Spalding of Sapaloe Island, Georgia, made the following entry in his diary: ''Bermuda-grass was brought to Savannah, Georgia, in 1751 by Governor Henry Ellis.'' This is the earliest record of the introduction of this grass, but its wide distribution in the tropical Americas suggests that it may have reached this hemisphere much earlier in the hay brought by the Spanish conquistadors to feed their horses. It occurs throughout the humid South and occupies more acres than any other pasture grass considered here. Other common names that it still bears are wiregrass, dog's tooth grass, devil grass, ''doob'' in India, and ''couch'' in Australia.

*b. Description.* Bermuda grass is a long-lived perennial that spreads by rhizomes, stolons, and seed. The leaves are short and are borne from stems characterized by alternate short and long internodes. This arrangement makes the leaves appear to be opposite on the stem. Seeds are borne on a cluster of racemes similar in appearance to crabgrass. The seed stalks reach a height of 6 to 12 in. Common Bermuda grass may be established by planting either seed or sprigs. Since the seed do not germinate at low temperatures, there is little to be gained from planting them before mean daily temperatures of 65 degrees Fahrenheit prevail (Nielsen, 1941). Hulled seed germinate more promptly than unhulled seed and should be used when early establishment is desired. More Bermuda grass is propagated by planting sprigs than by seeding. Farmers generally have better success by this method. The poor seeding habits of Coastal Bermuda makes it mandatory that it be established from vegetative material. This characteristic has stimulated the development of labor-saving machinery and methods which now make it possible to establish Coastal Bermuda vegetatively at less cost than planting seed of most other pasture grasses.

c. *Adaptation and Use.* Bermuda grass is best adapted to the states south of a line connecting the southern boundaries of Kansas and Virginia. In this area it occurs on more pasture acres than any other improved pasture species. Bermuda grass makes its best growth when mean daily temperatures are above 75 degrees Fahrenheit. Very little growth is made when these temperatures drop 10 to 15 degrees. Temperatures of 26 degrees to 28 degrees Fahrenheit usually kill the stems and leaves back to the ground.

Bermuda grass is more drought resistant than Dallis grass, carpet grass, or Bahia grass but does not make much growth under arid conditions. Consequently, unless irrigated, it is less productive in the arid Southwest than such native grasses as curly mesquite and buffalo grass.

Bermuda grass will grow on any moderately well-drained soil provided it has an adequate supply of moisture and plant nutrients. Although it will tolerate flooding for long periods, it makes little, if any, growth on waterlogged soils. Better growth generally has been observed on heavy soils than on light sandy soils, probably because heavy soils usually are more fertile and retain soil moisture better. When well fertilized, Bermuda grass has made excellent growth on deep sands. It it affected little by soil reaction and has made good growth on both acid and "over-limed" soils. Recent investigations at the Georgia Coastal Plain Experiment Station show that adding lime to soils having a pH below 5.5 favors the growth of this species.

Bermuda grass, when properly managed, is palatable, nutritious, and makes some of the best summer pastures in the South. Almost any legume grows well in association with Bermuda grass, provided the soil is well adapted to the legume and the lime and mineral requirements of the legume are met. The best Bermuda grass pastures usually contain annual lespedeza, crimson clover, or white clover as the associated legumes. The legumes, in addition to contributing to the forage consumed by the animals, can stimulate the growth of the Bermuda grass as much as a 400-lb.-per-acre application of nitrate of soda (Bledsoe and Sell, 1940). Although Bermuda grass will persist on poorer soils longer than some species, it makes little growth unless well fertilized, particularly with nitrogen. Recent studies (Burton *) with an improved Bermuda grass hybrid have shown that annual hay yields can be increased from 1 ton per acre with no nitrogen to 8 tons per acre with 400 lb. of nitrogen per acre per year. This treatment also increased the average protein content of the hay from 7.0 to 12.7 per cent. Turning old weed-infested sods helps to control perennial weeds and usually stimulates the growth of the grass.

Excellent hay can be made from common Bermuda grass where it grows tall enough to mow. Improved hybrids like Coastal grow tall enough to make hay under most environmental conditions. Good quality Coastal Bermuda hay (well fertilized and cut every five weeks) used as the sole source of feed for cows dropping calves enabled them to make a net gain of 47.2 lb during a 97-day wintering period. A similar lot of cows receiving only peanut hay showed a net loss of 49.4 lb. per head for the same period (B. L. Southwell,* Georgia Coastal Plain Experiment Station).

Bermuda grass is widely used for lawns, football fields, road shoulders, airfields, and many other turf purposes in the South. Heavy fertilization, particularly with nitrogen (a minimum of 100 lb. of N per acre per year) and frequent mowing are required to make the best turf. Annual ryegrass for winter lawns can be more easily established in Bermuda grass than in the sod of other turf grasses. Few turf species will stand greater wear or heal over more rapidly when injury occurs.

*Helminthosporium* sp. leaf spots reduce both the yield and quality of common Bermuda. Army worms seem to take Bermuda grass in preference to all other species. Perhaps the greatest fault of Bermuda grass lies in the difficulty of its control in cultivated fields. In the days of the mule and the single stock it was difficult to eradicate Bermuda grass and almost impossible to grow a cultivated crop successfully in a heavily infested field. Work stock, grazing common Bermuda grass pastures, undoubtedly spread it through the viable seeds in their droppings to all cultivated acres. It is easy to understand, therefore, why row-crop farmers developed a deep hatred for this grass. Modern tractor equipment has changed this situation. At the Georgia Coastal Plain Experiment Station 60 bushels of corn were produced per acre in 1949 on a heavy Coastal Bermuda grass, crimson clover sod (Burton and DeVane, 1950), suggesting that tractor equipment and improved strains of Bermuda grass may make corn-Bermuda grass rotations possible and profitable.

*d. Breeding.* Bermuda grass is a highly cross-pollinated tetraploid that seems to reproduce itself entirely by sexual means. Burton (1947), Avdulov (1928), and Darlington and Janaki Ammal (1945) found that *C. dactylon* contained 36 somatic chromosomes. Hunter (1943) reported 30 as the $2n$ number in the material that he examined. Burton

(1947) found difficulty in making positive counts due to chromosome fragments of varying size and number, some of which approached the size of chromosomes but concluded that the $2n$ number is probably 36 and several fragments. Hurcombe (1947) apparently considered these small elements to be small chromosomes and reported 40 as the somatic number.

Burton (1947) screened 5,000 open-pollinated seedlings from four superior clones that had been interplanted in a crossing block to facilitate natural crossing. Highly significant differences between clones were found in rate of spread, sod density, frost resistance, disease resistance, yield, percentage of weeds, percentage cover, seed yield and seed set, root-knot-nematode resistance, palatability, and longevity. Several clones demonstrated marked heterosis by outyielding both parents by significant margins. Two of these were given the names of Coastal Bermuda and Suwannee Bermuda and were released for farm use.

Coastal Bermuda (Burton, 1948c), named for the Station where it was developed, is well adapted throughout the Bermuda grass belt. It is an $F_1$ hybrid between Tift Bermuda (discovered by J. L. Stephens in an old cotton patch near Tifton, Georgia, in 1929) and an introduction from South Africa. It has larger and longer leaves, stems, and rhizomes and has produced about twice as much forage or beef as common Bermuda. It tolerates more frost, makes more growth in the fall, is more drought resistant, and is much more resistant to the *Helminthosporium* leaf spots than common Bermuda. It is immune to root-knot-nematode thereby facilitating the growth of root-knot-susceptible legumes (Burton *et al.,* 1946). Coastal Bermuda spreads faster, maintains a weed-free sod longer, but is easier to control than common Bermuda. Since it rarely produces viable seed, it must be propagated vegetatively. Coastal Bermuda is an excellent hay plant, giving high yields of easily cured hay.

Suwannee Bermuda (No. 99) is a hybrid similar to Coastal Bermuda but is better adapted to light sandy soils. Hodges * on a sandy soil at Ona, Florida, obtained 157 lb. of beef gain per acre from Suwannee as compared with 132 lb. of gain per acre from Coastal Bermuda. It sods over more slowly than Coastal but once established will often produce more hay per acre. Suwannee does not tolerate close grazing as well as Coastal Bermuda. It is being planted largely on the light sands of Florida.

Tifton 57 is a turf Bermuda grass developed at the Georgia Coastal Plain Experiment Station. It is more disease resistant, more frost tolerant, and makes a much denser turf than common Bermuda. It resists the invasion of weeds and is better able to crowd out common Bermuda than other strains tested to date. It is suitable for golf greens as well as lawns and other turf purposes.

All the improved Bermuda grass varieties developed to date seed very poorly and must be propagated vegetatively. The Georgia Crop Improvement Association has developed standards for, and is certifying sprigs of, these Bermudas.

### 3. *Carpet Grass*

*a. Origin and History.* Carpet grass, *Axonopus affinis* Chase, a native of Central America and the West Indies has been in the United States so long that no record of its introduction may be found. Its ability to grow on poor soils and withstand close grazing has enabled it to spread throughout the Coastal Plain wherever the native vegetation has been closely grazed. It now occurs in the tropics of both hemispheres.

*b. Description.* Carpet grass is a summer-growing perennial that spreads by stolons to form a dense sod. Most of the leaves are basal and rarely exceed a height of 6 to 8 in. The slender flower stalks reach a height of 12 to 18 in. and give rise to an abundance of small seed (1,350,000 per pound) throughout the summer. It is generally established from seed, 5 to 10 lb. per acre being the usual rate for pasture purposes.

*c. Adaptation and Use.* Few introduced grasses are so well adapted to the virgin soils of the Coastal Plain. Although carpet grass lacks drought resistance and makes its best growth on the lowland soils, it also comes into upland areas when the soil fertility is low. That carpet grass will respond to fertilizer has been well demonstrated by Blaser and Stokes (1943), who doubled its yield and increased its percentage content of phosphorus, potassium, calcium, and nitrogen by applying lime and complete fertilizer. Carpet grass is little injured by the attacks of insects and diseases.

Carpet grass is the most common pasture grass in Florida and the lowlands of the Coastal Plain. Most of it exists in pure stand, due to lack of fertilization, and makes poor quality grazing. Good summer grazing can be had, however, by applying adequate supplies of minerals and introducing some legume. Common lespedeza and white clover are the legumes most generally used. Close grazing or scarification of the sod is necessary to facilitate the establishment of the legumes. Most lowland pasture mixtures that have included Dallis grass and white clover soon revert to pure carpet grass if the fertilization program is discontinued. One of the serious pasture problems in the lower South is that of keeping carpet grass from crowding out Dallis grass and the legumes. Keeping the fertility level of the soil high enough to favor the growth of Dallis grass and the legumes has been the principal method used in solving this problem. Preliminary studies by Robinson and Burton * on carpet grass turf suggest that liming to raise the pH of the soil above 7.0 may offer a more effective solution to the problem. Carpet grass growing on a Tifton sandy loam having pH slightly above 7.0 has become chlorotic (corrected by spraying with iron sulfate) and has made very poor growth, allowing Bermuda grass to invade the area and crowd it out. Dallis grass, Bermuda grass, and may of the clovers grow well at pH 7.0.

Although carpet grass is not a very nutritious grass, it does contribute to the range grazing in the Coastal Plain by furnishing pasturage during the summer and early fall when the native grasses are tough and unpalatable. The continued close grazing that it receives where it occurs in the range probably improves its quality.

Carpet grass makes a good lawn and turf grass in the lower Coastal Plain. It may be established from seed, makes a dense turf that will tolerate moderate shade, and will grow with little fertilization or care other than mowing. Its tall seed heads that are produced continuously throughout the summer cannot be kept down with a reel lawn mower, unless mowed frequently, and may give the lawn a ragged appearance. It is well suited for turfing road shoulders in this area and is being used extensively for this purpose.

*d. Breeding. Axonopus affinis* collected near Tifton contained 80 somatic chromosomes (Burton, 1942). So far as the writer is able to ascertain, no varieties of carpet grass are in existence and no breeding work has been done with the species.

### 4. *Centipede Grass*

*a. Origin and History.* Centipede grass, *Eremochloa ophiuroides* (Munro) Hack., is a native of southeastern Asia and probably originated in Southern China. In 1916 Frank N. Meyer, Plant Explorer for the U. S. Department of Agriculture, made his fourth trip into China—this time South China. Meyer never came out, and his fate still remains a mystery. Eventually some of his luggage came down the river in a small boat. In one of his trunks were several small packets of seed that gave rise to the first centipede plants introduced into the United States.

*b. Description.* Centipede grass is a low-growing perennial that spreads rapidly by stolons. Its seed are borne on erect, slender spikes that rarely extend more than 8 in. above the ground. The very dense sod made by its moderately narrow leaves make it difficult for other plants to grow in association with it.

*c. Adaptation and Use.* Few grasses are so well adapted to southern soils. It will grow on heavy or light soils, wet or reasonably dry soils with little or no plant food other than that supplied by nature. It has survived the winter as far north as northern Alabama and Raleigh, North Carolina, but cannot be safely planted much farther north. It will turn brown with the first frost and makes little growth thereafter until spring.

Grazing studies (Stephens, 1942, and others not published), with the exception of those reported by Ritchey and Henley (1936), have proved that centipede grass is a very poor pasture plant. Legumes and other grasses usually are soon crowded out by centipede grass and poor animal gains result. Chemical analyses of centipede grass clippings, even in the young stages of growth, show them to be low in protein and unusually high in crude fiber. It is obvious, therefore, that centipede grass should not be used for pastures. Since it produces seeds that germinate well after passing through the digestive tract of cattle, it cannot be safely planted, even for lawns, on livestock farms.

The average homeowner who wants a good lawn with little care has found centipede grass an excellent choice. Although regular mowing is required to make the best quality turf, it can be left unmowed for a month or more without becoming too ragged in appearance. Moderate applications of fertilizer and nitrogen are required to make the best lawns, but reasonably satisfactory turf can be had with no fertilizer at all. Heavy applications of nitrogen over a period of several years cause centipede grass to die out. A satisfactory explanation for this response has not been discovered. Rhizoctonia has been found on centipede grass but is not believed to be common. No other diseases have been observed, and insects, including Army worms, have invariably refused it.

Practically all the centipede grass lawns in the South have been established by planting sprigs, because commercial sources of seed have not been available. Sprigs are sold by the bushel, and a bushel usually contains 500 to 600 sprigs. Sprigs planted 12 in. apart in 12-in. rows in the spring often establish a good sod by fall.

For many years the seed trade believed that centipede grass would not produce seed. Burton (1950) has shown, however, that good yields of high quality seed can be produced by proper fertilization and management.

A study of rates of nitrogen and dates of its application revealed that 60 lb. of nitrogen per acre applied in early April was the most profitable combination, giving 155 lb. of cleaned seed per acre over a three-year period.

Mowing the turf until heads began to form (July 1) was necessary when nitrogen was applied. Since the heads do not shatter or lodge, the entire season's production (heads are formed from July 1 to October

15) can be accumulated before harvesting, provided traffic is kept off the turf. Developments in the seed trade indicate that centipede grass seed should be on the market in volume in two or three years. Once seed become available, centipede grass will find a wide use on schoolyards, parks, playgrounds, golf courses, and other places where low-cost turf is required.

*d. Breeding.* Nothing is known concerning the method of reproduction of centipede grass. One of the introductions grown at Tifton, Georgia, does not develop the red anthocyanin characteristic of other centipede grass introductions that have been observed. The centipede grass that has been propagated vegetatively for lawns appears to be of one (the red anthocyanin) type. No named strains or varieties exist at this time.

### 5. *Dallis Grass*

*a. Origin and History.* Dallis grass, *Paspalum dilatatum* Poir., introduced into the South from Argentina or Uruguay about the middle of the last century, is named after A. T. Dallis of LaGrange, Georgia, who grew it extensively (Hitchcock, 1935). It is now widely distributed throughout the Gulf States and is widely recommended for pasture purposes.

*b. Description.* Dallis grass is a perennial, decumbent, bunch grass that produces a great mass of basal leaves. Its seeds are borne on semierect ''stemmy'' culms that reach a height of 24 to 36 in. when mature. Like many other southern grasses, Dallis grass produces heads from May until late October. It is usually established from seed in the United States by planting 10 to 20 lb. of seed per acre. In parts of the East Indies and the Hawaiian Islands sprigs are planted to insure more successful establishment.

*c. Adaptation and Use.* For the Black Belt and Delta region where the soils are quite fertile, on the heavier soils in the Piedmont, and in the lowland areas of the Coastal Plain where a rather high fertility level is maintained, Dallis grass is one of the best grasses that can be grown. It will do much better on wet soils than Bermuda grass. Lovvorn (1944b) found it as productive as common Bermuda grass when grown on a well-drained Coastal Plain soil in North Carolina. In his test a mixture of Dallis grass and Kobe lespedeza outyielded common Bermuda grass and Kobe lespedeza by about 8.0 per cent over a four-year period. Adding lespedeza to pure stands of either grass nearly doubled the yields. Its growth is usually favored by applications of complete fertilizer high in nitrogen. Although lime generally is considered favorable for growth, Lovvorn (1944a,b) found that pure stands of Dallis grass growing in a Norfolk soil (pH 5.5) failed to respond to lime. Ergot, *Claviceps paspali,* destroys many of the florets and is partially responsible for the poor quality of much Dallis grass seed produced in this country. Cattle grazing Dallis grass pastures, in which many ergot infested heads have accumulated, are often poisoned from eating the heads. Anthracnose, *Colletotrichum graminicola,* attacks the leaves of Dallis grass, particularly when the top growth has been allowed to accumulate for seed production. As a result, most of the leaves are killed and, under severe epiphytotics, the plants may die.

Dallis grass is palatable and nutritious and makes an excellent pasture when grown in association with lespedeza or clover, usually white clover. In the Coastal Plain of North Carolina (Lovvorn, 1944b) lespedeza grew better in association with Dallis grass than with Bermuda grass. Mayton (1935) observed the reverse to be true at Auburn, Alabama. Differences in management could have accounted for these conflicting findings. It will tolerate moderately close grazing and should be grazed or mowed frequently enough to prevent the accumulation of mature seed stalks and dead leaves. To insure successful establishment, good seed should be planted (preferably with a cultipacker) on a well-prepared seed bed in the early spring, or late fall in the extreme south. Grazing or mowing from the time the Dallis seedlings and weeds begin to appear (to reduce weed competition and anthracnose to a minimum) has given better establishment than the old practice of keeping animals off the pasture during the first year (Burton *).

Dallis grass makes poor quality hay and is rarely used for that purpose. Its coarse growth and profuse heading habit make it one of the worst pests in lawns, fairways, and other turfed areas.

*d. Breeding.* The method of reproduction in Dallas grass has not been clearly established. Burton (1945) found that 19 out of 24 Dallis grass seed sources gave rise to progenies so similar in type that they could not be separated one from another. Statistically significant differences in forage yield, anthracnose resistance, self fertility, heading date, ergot resistance, and longevity were obtained, however, between these 19 seed sources, indicating that they were not identical in their genetic constitution. The remarkable uniformity of the spaced plants coming from each of these seed sources permitted the differences between the sources to be significant. Burton * found no natural hybrids in open-pollinated seed harvested from two clones that had been interplanted, indicating that these two clones were not cross-pollinated. Numerous attempts to hybridize superior local with introduced Dallis grasses at Tifton, Georgia, have usually given rise to plants like the female parent even when the most careful hybridizing techniques have been used. Only two hybrids have been obtained to date. One of these gave rise to a uniform progeny like the $F_1$ parent, whereas the other segregated profusely. These findings point to apomixis as the main method of reproduction in Dallis grass. Dallis grass is a tetraploid having 40 chromosomes as the $2n$ number (Burton, 1940b). Smith (1948) has found that common Dallis grass is consistently irregular at meiosis, having typically 30 elements that may be classified cytologically as $10_{II}$ $10_I$ $10_I$. He concludes on the basis of his cytological studies that it is of hybrid origin and that it reproduces by agamospermy, a form of apomixis. Owen (1949) reports that nearly one-fourth of a group of 144 progenies of Dallis grass planted in 1944 segregated for plant type. Significant differences in the seed yield between progenies of sister plants were also observed. He also found significant differences in forage and seed yield between different seed sources. It is evident from the discussion above that Dallis grass is both apomictic and sexual in its reproduction. Further study will probably reveal that it is much like Kentucky bluegrass, some plants reproducing entirely by apomixis, others sexually, and still others by both means. The relative proportion of these types cannot be predicted at this time.

Increased forage and seed yields and resistance to ergot and anthracnose have been the major objectives in the breeding of this grass. By selecting within native seed sources (ecotypes) Owen (1948) isolated B-230 and 430 that carry some ergot resistance, produce more and better quality seed, and give higher yields of forage. These selections are being increased for distribution. Burton (1943b) hybridized Dallis grass with a *Paspalum urvillei* x *Paspalum malacophyllum* hybrid and obtained a number of trihybrids ($2n = 60$) carrying a chromosome complement of each parent. These hybrids were highly resistant to anthracnose and were much more vigorous than Dallis grass. Two of them were completely immune to ergot. All were almost completely sterile, and little progress has been made toward increasing their fertility. Since they are bunch grasses, vegetative propagation has not been considered practicable. Bennett (1948-1949) has selected plants from a Dallis grass x *Paspalum malocophyllum* cross that are very promising in as much as they set seed freely and are immune to ergot. The best of these individuals are being increased for further testing.

### 6. *Italian Ryegrass*

*a. Origin and History.* Italian ryegrass, *Lolium multiflorum* Lam., originated in the Mediterranean region and probably was first cultivated in northern Italy. Records indicate that it was known in Switzerland and France as early as 1820. There is reason to believe that it was brought to America by European immigrants early in the history of this country.

*b. Description.* Italian ryegrass is an annual bunch grass that usually attains a height of 2 to 3 ft. when mature. Its rolled leaf bud, cylindrical stem, and yellowish green base distinguish it from perennial ryegrass which has a folded leaf bud, flattened stem, and reddish base. The edgewise placement of the large spikelets on the rachis furnishes a characteristic marker for the ryegrasses. The short awns that characterize Italian ryegrass seed are absent from the seed of perennial ryegrass. Most of the annual ryegrass seeds sold in the United States carry the names ''domestic'' or ''common'' ryegrass because they contain a mixture of types. Italian ryegrass is propagated entirely from seed, rates ranging from 20 lb. per acre for pastures to over 100 lb. per acre for lawns.

*c. Adaptation and Use.* Italian ryegrass requires a cool, moist climate. It winterkills in the northern states and dies out during the summer in the South. It makes rapid growth on fertile soils high in nitrogen but produces little on poor soils. At Tifton, Georgia, in the winter of 1948 when given only 40 lb. of nitrogen per acre, it produced only about half as much dry matter as Abruzzi rye. When both grasses received 200 lb. of nitrogen per acre, it produced 22 per cent more forage than Abruzzi rye (Burton *). Ryegrass seed is produced in the Pacific Northwest, where it is also used for hay and pasture. In the South it is used for annual winter grazing and winter turf. When grown alone in the Coastal Plain on soils of only moderate fertility, it has produced less beef than oats or rye (Burton *et al.*, 1949). LaMaster *et al.* (1950) reported that during a three-year period 1947-1949 cows grazing a mixture of domestic ryegrass and crimson clover produced 21.9 per cent more 4 per cent fat-corrected milk than the barn-fed controls. During the test it averaged 3,000 lb. per acre of T.D.N. (total digestible nutrients) annually over a 167-day period and had an annual net cash value of $65.27 per acre.

In order to have green lawns during the winter months, many southern homeowners plant domestic ryegrass on their lawns in the early fall. Considerable artificial watering usually is required for early establishment. Heavy fertilization and frequent mowing are essential if good winter lawns are to result. Although this practice weakens the summer lawn, the damage generally is not serious if the ryegrass is mowed frequently. Most southern golf greens are planted to ryegrass in the fall at a rate of 40 to 50 lb. per 1,000 sq. ft. to make a green playing surface during the winter months. When properly managed, it makes an excellent playing surface. Domestic ryegrass dies out in early summer and must be reseeded each fall. Rust (*Puccinia* sp.) often attacks ryegrass in the late spring, gives it an ugly appearance, and hastens its death.

*d. Breeding.* Italian ryegrass is a diploid having 14 chromosomes as the $2n$ number (Avdulov, 1928). The species is quite variable, indicating that it reproduces sexually and is highly cross-pollinated. Vinall and Hein (1937) have pointed out that selfing this grass results in extreme loss of vigor. Several varieties have been developed in foreign countries but have never become important in the United States. Among these are Western Wolths ryegrass, a rapidly growing annual, developed in Holland and Wimmera ryegrass, another annual, that originated in Australia. So far as the writer is aware, there has been no attempt made by workers in the United States to improve this species by breeding.

### 7. *Johnson Grass*

*a. Origin and History.* About 1830 a South Carolina cotton planter was sent by Governor Means of that state to Turkey to instruct the Turks in cotton culture. Impressed with a vigorous Turkish hay grass, he brought back a small quantity of its seed and distributed it among his friends. Called Means' grass for a number of years, this grass, *Sorghum halepense* (L.) Pers., was later named Johnson grass after Colonel William Johnson who grew it extensively on his plantation near Selma, Alabama. Cattlemen soon carried this much publicized grass into every section of the South. As it escaped into cotton fields, planters discovered that this ''wonder grass'' was the worst weed that they had ever known. In the Black Belt of Alabama and on some of the fertile bottom lands, Johnson grass is credited with having completely taken over many cotton farms, forcing the landowners to seek a new livelihood. Since Johnson grass makes good hay, a number of these farmers turned to hay production and enjoyed a fair measure of prosperity as long as there was a market for Johnson grass hay. In recent years the demand for Johnson grass hay has fallen, and its sale has been restricted by legislation until these hay farmers have of necessity turned to livestock as a means of marketing their grass. Many of these farmers have found that a profitable livestock enterprise can be built around the use of this grass for most of their livestock feed.

*b. Description.* Johnson grass is a perennial sorghum that resembles Sudan grass in its aboveground appearance. On rich land its stems, the size of a lead pencil, may reach a mature height of 6 ft. or more. Below the surface of the ground, it produces numerous fleshy rhizomes that are sometimes found as deep as 24 in. below the surface. Its large open panicles bear an abundance of seed, some of which lie in the soil for several years before germinating. New pastures of Johnson grass are established by planting 20 to 30 lb. of seed per acre.

*c. Adaptability and Use.* Johnson grass occurs as a perennial as far north as southern Illinois and Indiana. It thrives only where moisture is abundant and is restricted to irrigated lands and ditch banks in southwestern United States. It is a rich land crop and is usually found on the heaviest most fertile soils in the South. It is rarely found on the sandy soils of the Coastal Plain.

Johnson grass is highly palatable and nutritious and makes excellent grazing if properly managed. Since continuous grazing reduces growth, thins stand, and allows weeds to take over, rotational grazing is usually recommended for best results. Plenty of plant food, particularly nitrogen, is required for maximum production. Johnson grass pastures can be greatly improved by planting Caley peas, sweet clover, or even white clover in them. Baker (1950) has developed an excellent system of working Johnson grass into a year-round feed supply for a process milk dairy herd. This system consists of cutting the first growth for hay, using the aftermath for supplemental grazing if necessary, but more frequently grazing the frost-killed grass in winter to supply winter roughage.

Johnson grass, like the other sorghums, carries a glucoside that breaks down under certain circumstances releasing the poison prussic acid. Young shoots usually contain the highest concentration of this glucoside. Prolonged drought, that stunts the growth, increases the concentration of the prussic acid glucoside in all plant parts. The conditions under which Johnson grass is grazed in the South are such that authentic cases of prussic acid poisoning in cattle grazing it are rare. Nevertheless, it is advisable to keep animals off pure stands of very young or drought-stunted Johnson grass. To make the best quality hay, Johnson grass should be cut just before the first heads appear. As many as four cuttings per year may be taken under favorable growing conditions. The coarse stems and high moisture content of Johnson grass make it difficult to cure and increase the losses from rains that fall during the curing process. Stockmen in the South generally agree that good Johnson grass hay has a higher feeding value than timothy hay.

Clean fallowing from July 1 to frost usually will exhaust the reserves in the rhizomes and kill the plants that were present in the field. It will not, however, destroy all the seeds that may be present in the soil; thus it becomes necessary to eliminate the young plants from such seeds over a period of several years if complete eradication is desired. Since the droppings of animals grazing mature Johnson grass plants as hay will contain viable seeds (Burton and Andrews, 1948), care should be taken to keep such manure off clean fields or fields that are being fallowed. Continuous heavy grazing will weaken the plants and may logically precede fallowing in the control schedule.

*d. Breeding.* Johnson grass is a tetraploid, $2n = 40$ (Katterman, 1930). The variability exhibited by spaced seedling populations of this grass indicates that it reproduces largely by sexual means and that it is highly cross-pollinated. Bennett (1948, 1949) found 12 per cent of his Johnson grass seedlings were self-fertile, 8 per cent were partially self-fertile, and 80 per cent were self-sterile. He observed striking differences in amount of spreading, disease resistance, date of maturity, ability to withstand mowing, and yield. One of his selections that is self-fertile and breeds true for its superior traits is being increased for probable distribution.

The first natural Johnson grass sorghum hybrid was found on a farm near Chillicothe, Texas, in 1912 (Vinall and Getty, 1921). Several other natural crosses were found, and artificial crosses were made in 1912 and 1913. Extreme variation was observed in advanced generations of these hybrids and some promising individuals were observed. None of them ever reached commercial importance, however. Bennett (1948, 1949) has recently hybridized Hodo sorghum and Johnson grass and has segregates from this cross that offer promise.

### 8. *Kentucky Bluegrass*

*a. Origin and History.* Kentucky bluegrass, *Poa pratensis* L., a native of the Old World, probably was first brought to the United States by the early colonists. Its present wide distribution throughout the northern States and the mountainous and cooler localities farther south proves that it is unusually well adapted to the soil and climate of this region.

*b. Description.* Kentucky bluegrass is a long-lived perennial. It spreads slowly by short underground rhizomes and forms a dense sod of basal leaves that seldom grow over 8 in. high. Its culms that are usually produced in June attain a height of 18 to 24 in. It is propagated entirely by seed, generally requiring rates of 5 to 10 lb. per acre to give a good stand.

*c. Adaptation and Use.* Kentucky bluegrass requires a cool climate and usually makes little growth during the hot summer months. Its use is restricted, therefore, to the mountains and northern part of the humid South. It makes its best growth on well-drained fertile soils that have been limed. It is a very palatable and highly nutritious grass and is able to withstand close grazing more successfully than many other pasture plants. As a consequence, it occurs in many over-grazed pastures that have been given little care. White clover is the legume most frequently grown with it, and the combination makes excellent grazing in the spring and fall. Its failure to make good growth in the summer is causing it to be replaced by bromegrass, orchard grass, and tall fescue. Woodhouse * has found orchard grass and tall fescue much more productive than Kentucky bluegrass in the Tidewater, Piedmont, and mountain sections of North Carolina. Its aggressiveness and its ability to withstand close grazing enable it to crowd out the more productive grasses to the extent that pasture renovation often consists of measures to eliminate enough of the bluegrass to permit the introductions of other grasses. It is used for lawns and turf in the northern part of the South and is used as a shade grass in lawns as far south as Atlanta. Liberal applications of lime and fertilizer, particularly nitrogen, are necessary to make good turf from this grass.

*d. Breeding.* Cytogenetic studies by Akerberg (1939), Brittingham (1943), Nielsen (1945), and others have shown that some Kentucky bluegrass selections reproduce completely by apomixis, others reproduce sexually, and others give rise to a mixture of sexual and apomictic offspring. Smith and Nielsen (1946) proved that selected plants followed the same pattern of reproduction whether self- or open-pollinated.

Kentucky bluegrass is a highly variable species. In the third year of clipping, Myers and Garber (1942) obtained significant yield differences between 81 selected plants grown in clonal plots. Myers and Sprague (1944) compared 13 selections and two commercial seed lots and concluded that there was no noticeable tendency for differences among strains to disappear in the third year as compared with the first year. In Wisconsin 32 bluegrass selections were superior to commercial bluegrass in the first year, but only one continued to be superior in the third year of the test (Ahlgren *et al.*, 1945). These disconcerting results indicate some of the problems that plague the grass breeder. Results with Bermuda grass at Tifton, Georgia, indicate that the yield differences between selected clones diminish unless heavy applications of fertilizer, particularly nitrogen, are made. Much information concerning the breeding behavior of bluegrass has been accumulated, and superior plants have been isolated. None of them, however, has been increased for pasture purposes, probably because other grasses such as brome, tall fescue, and orchard grass have recently been found to be superior in the bluegrass region.

A superior turf strain bearing the name Merion (B-27) bluegrass is being increased and distributed. This strain originating at the Merion Golf Club, Ardmore, Pennsylvania, has been shown to be superior in appearance, rate of spread, density, resistance to weed invasion, and

*Helminthosporium* leaf spot, and tolerance to heat and drought. Early tests indicate that Merion bluegrass is well adapted throughout the bluegrass belt and should help to solve the turf problems in that region.

### 9. *Napier Grass*

*a. Origin and History.* A native of tropical Africa, Napier grass, *Pennisetum purpureum* Schumach., is named for Colonel Napier who established its agricultural value in South Africa early in the twentieth century. Introduced into the southernmost sections of the United States in 1913, it soon met with much favor. A number of plantings were made by dairymen around the larger cities in Florida and for several years Napier grass was heralded as a great discovery. This interest soon died, however, and comparatively few acres of this grass can now be found in the continental United States. The eyespot disease caused by *Helminthosporium sacchari* was largely responsible for the early failures. The labor and expense associated with the establishment and proper management of Napier grass have been largely responsible for the reduction in the acreage devoted to this grass.

*b. Description.* Napier grass is a coarse perennial bunch grass that resembles sugar cane in appearance. Its stems, often 1 in. in diameter, attain a height of 8 to 10 ft. when mature. Its leaves are more than 1 in. in width and are 2 to 3 ft. long. Adventitious buds at the nodes give rise to shoots with clusters of leaves when Napier grass is grazed. Its small seeds enclosed in a cluster of hairy bracts are borne in terminal spikes, 5 to 10 in. long. The difficulties of harvesting, processing, and planting Napier grass seed explain why it is propagated by planting divided crowns or canes. The canes are usually laid flat in a furrow and covered or are cut into three-node sections and are pushed into the ground so that the top node protrudes above the surface of the soil.

*c. Adaptation and Use.* Winter temperatures restrict Napier grass to the Coastal Plain of the Gulf States and regions having equally mild winters. Like most other tropical plants, it makes its best growth when temperatures are high and soil moisture is abundant. It will make good growth on most any well-drained soil that contains or is supplied with plenty of plant nutrients. In most of the tropical areas where Napier grass is grown for livestock feed, it is managed as a soiling crop. In Hawaii, Ripperton and Akamine (1938) have found it the most productive of all soilage crops. A three-year study of the effect of frequency of clipping upon the yield, quality, and stand of this grass (Wilsie *et al.*, 1940) revealed that cutting at 6-week intervals thinned stands, increased weed competition, gave the lowest total yield, and reduced the vigor of the stools. Cutting at 8-week intervals allowed the plants to retain their stand and vigor, and gave higher yields of palatable herbage and protein than clipping at 10, 12, or 14-week intervals. The average annual (52 weeks) production of dry forage was 12.2 tons per acre when clipped at 8-week intervals and 19.4 tons per acre when clipped at 14-week intervals. These results indicate the necessity of grazing enough pastures rotationally to permit a good recovery period after grazing, if stands are to be maintained and maximum yields are to be had. Blaser *et al.* (1942) grazed five paddocks of Napier grass growing on a Norfolk soil at Gainesville, Florida, for three years. Fertilization consisted of 400 lb. per acre of 5-7-5 in March and later nitrate of soda top dressings, totaling 300, 375, and 210 lb. per acre during the three years of the test. Each pasture was grazed five to seven days and rested 20 to 30 days. During the three-year period these pastures averaged 231 animal grazing days per acre from May 1 to October 15 and produced 369 lb. of beef gain per acre. The animals made an average daily gain of 1.60 lb. and never produced less than 1 lb. gain per day throughout the test. These results indicate that Napier grass is an excellent pasture grass if managed properly.

Shealy *et al.* (1941) compared Napier grass silage (cut just before bloom) with sorghum silage (cut when seed were in the dough stage) and sugar cane silage (cut in late fall) as roughages for steers being fattened on a concentrate of two parts of ground snapcorn and one part of cotton seed meal. They concluded, ''If a value of 100 is assumed for sorghum silage on a comparative feeding basis, then Napier grass silage is valued at 75 and sugar cane silage at 70 as a roughage for fattening steers.''

*d. Breeding.* Napier grass is a tetraploid possessing 28 somatic chromosomes (Burton, 1942). The variability exhibited by seedlings of this grass indicates that it reproduces sexually and is highly cross-pollinated. Its flowering habit (stigmas are exserted several days before the anthers) greatly facilitates natural crossing and artificial hybridization. Breeding for resistance to *Helminthosporium sacchari* was one of the first objectives in the improvement of this grass. This disease created great losses in Georgia and Florida in the 1930's. Burton * and Ritchey * both succeeded in isolating resistant clones, which soon solved this problem. This disease hit all the Hawaiian Islands simultaneously for the first time in 1940. (Takahashi *et al.*, 1940). These workers observed that Merker grass (a woodier stemmed strain) and some of the Napier x Merker hybrids were highly resistant to the disease. These resistant clones were rapidly increased and released to replant fields killed out by disease.

Burton * found Napier grass clones varied significantly in cold resistance, leafiness, earliness, and yield. Marked heterosis resulted from some hybrid combinations. The best of these hybrids, Georgia 208 x 1, has produced 77 tons of green forage per acre per year in Puerto Rico and has outyielded all other Napier grass strains under test there.

Napier grass was first hybridized with pearl millet (*Pennisetum glaucum* (L.) R.Br.) in the fall of 1941 (Burton, 1944). Using Napier grass as the female parent and two late maturing strains of pearl millet as the male (Burton) obtained 134 $F_1$ hybrids, 37 per cent of which were chlorophyll deficient and yielded only about 10 per cent as much as green hybrids. Striking variations in cold resistance, branching, leafiness, and yield were observed. Sixty per cent of the hybrids survived 15 degrees Fahrenheit, but most of them were less vigorous in the following spring than Napier grass. Those hybrids examined cytologically possessed 21 somatic chromosomes, the reduced complements of the two parents. These hybrids were highly sterile and died out at Tifton during the following two winters. Several of the most promising plants were sent to Puerto Rico and Panama for further study. Van Horn (1946, 1948) made the Napier x Millet cross and its reciprocal in Hawaii in 1945. His results using Napier grass as the female were similar to those reported above. When millet was the female, most of the hybrids had less than 21 chromosomes and resembled pearl millet. One hybrid with 28 chromosomes was reported. Selfed and millet backcrossed progenies resembled pearl millet and had little value. Several of the backcrosses to Napier grass were highly resistant to *Helminthosporium sacchari,* were devoid of hairs, produced dense stools desirable for machine harvesting, and outyielded Napier grass in preliminary tests.

### *10. Orchard Grass*

*a. Origin and History.* Orchard grass, *Dactylis glomerata* L., is at home in Europe where it is generally called cocksfoot. Available records indicate that it was first cultivated in North America in Virginia in 1760. It proved well adapted to the southern half of the bluegrass-timothy belt and spread over this area until today it is considered the most important pasture grass in much of this region.

*b. Description.* Orchard grass is a perennial bunch grass that has neither rhizomes nor stolons. Its folded basal leaves generally are so dense as to give it a tussock appearance as it occurs in pastures. Its characteristic clustered inflorescence is born on culms ranging from 18 to 48 in. in height. It is propagated entirely by seed.

*c. Adaptation and Use.* Orchard grass is not as winter hardy as bromegrass or timothy, but few cool-season grasses will tolerate as much summer heat. Consequently, it is one of the best pasture grasses for the upper South. It tolerates moderate frosts and, in this region, makes some growth during warm periods throughout the winter. Orchard grass is adapted to a wide range of soil conditions and will succeed on poor soils where Kentucky bluegrass usually fails. Although its peak production comes in the spring, it supplies more summer grazing than any other cool-season grass with the possible exception of tall fescue.

Orchard grass and annual lespedeza make a very satisfactory pasture combination on soils of moderate fertility. The use of such legumes as ladino clover and alfalfa with orchard grass, where they can be grown, will increase the total grazing and also extend the grazing season. In the lower Piedmont of North Carolina, Chamblee * has found that an orchard grass-ladino clover mixture will produce 58 per cent more dry matter per year than an orchard grass-Kobe lespedeza mixture receiving the same fertilizer treatments. Ladino clover during one growing season removes roughly twice as much calcium and phosphorus and more than three and one-half times as much potash as annual lespedeza (Woodhouse, 1950). This means that orchard grass-Ladino clover pastures will require much heavier fertilization than orchard grass-lespedeza pastures for optimum growth.

Orchard grass, like all other grasses, responds to nitrogen fertilization. In northern Virginia the application of 100 lb. of nitrogen per acre increased the annual yield of hay from 1,099 lb. per acre to 5,099 lb. per acre (Jones *et al.*, 1947). It also increased the protein content of the hay from 9.83 per cent to 11.37 per cent. In North Carolina, Chamblee * obtained with no nitrogen annual dry forage yields ranging from two to three and one-half tons per acre from a mixture of orchard grass and ladino clover, indicating that adding ladino clover to orchard grass will result in the production of more forage than adding 100 lb. of nitrogen per acre.

When grown in association with a legume, such as ladino clover, and cut at the early heading stage, orchard grass makes excellent hay or silage. Early cutting is necessary in order to keep the grass from choking out the clover.

*d. Breeding.* Although commercial orchard grass is a tetraploid $2n = 28$ (Davies, 1927), diploid forms have also been isolated. Muntzing (1937) observed that the pollen fertility was high in both of these groups, but the tetraploids were twice as vigorous as the diploids. He found the pollen fertility to be low in those plants having somatic chromosome numbers other than 14 and 28. The regular occurrence of quadrivalents at meiosis and the genetic ratios obtained from crosses involving lethal chlorophyll deficients caused Myers (1940, 1941) to conclude that 28 chromosome orchard grass is an autotetraploid. Variations ranging from complete self-fertility to complete self-sterility have been observed in selections of this grass (Stapledon, 1931; Nilsson, 1934; Schultz, 1941). Nilsson (1934) found large differences in the height of plants in selfed progenies. Reductions in vigor of 50 per cent or more in two-year and three-year selfed progenies of orchard grass were reported by Stapledon (1931). Although selfing reduced the average yield, height, and number of culms in orchard grass, a number of clones were found in the two-year selfed group that were fully equal to superior individuals in the open-pollinated group (Shultz, 1941). A very high correlation coefficient of 0.905 was obtained between the mean winter injury of parental clones and inbred progenies of orchard grass (Myers and Chilton, 1941). These workers observed that inbred progenies segregated for winter injury. They also found no relation between *Puccinia graminis* infection and degree of winter injury.

It is apparent from the information reported above that orchard grass is a highly variable cross-pollinated species that reproduces sexually. The opportunities for improving this important grass by breeding are great, and the work now under way with this species should result in the release of superior varieties in the near future. There are no American varieties in commercial production at the present time and European varieties, such as S-143 from Wales and Brage from Sweden, appear to be inferior to common orchard grass in this country.

### *11. Pangola Grass*

*a. Origin and History.* In 1935 the Division of Plant Exploration and Introduction in the U.S. Department of Agriculture received 30 samples of *Digitaria* species collected by an English worker in South Africa. These were planted at the Georgia Coastal Plain Experimental Station at Tifton, Georgia, and the Florida Experiment Station at Gainesville, Florida. Striking variations were observed in most of the characteristics of these grasses. One carrying the scientific name *Digitaria decumbens* Stent and the P.I. No. 111,110 looked very promising at both stations and was increased for grazing tests at Tifton in the summer of 1939. The minimum temperature of 12 degrees Fahrenheit the following winter completely killed out this new planting and made it seem unwise to do further work with a species that could be completely killed by severe winters. At Gainesville, Florida, the grass survived the winter of 1939-1940, continued to show promise, was named Pangola grass for the Pangola River in South Africa where it was found, and was released to Florida farmers (George E. Ritchey *). Today Pangola grass is one of the most popular grasses being planted in peninsular Florida.

*b. Description.* Pangola grass is a perennial that resembles annual crabgrass very closely. It differs in that it has long rapidly growing stolons (aboveground stems) and produces no viable seeds in the many heads that are formed. It is propagated by planting sprigs or mowings. Top growth that has become too tough for hay or grazing makes the best planting stock. The most common planting method consists of scattering this material and disking it in with a tandem disk harrow. The soil must be moist for this method to succeed. Following the disk harrow with a cultipacker usually aids establishment.

*c. Adaptation and Use.* Pangola grass is a warm-season grass that would appear to be limited to those sections of the deep South where winter temperatures do not drop below 12 to 15 degrees Fahrenheit. It makes its best growth on well-drained moist soils, but will survive both flooding and drought. It is highly palatable and is readily eaten even after being damaged by frost. A three-year grazing test at Gainesville, Florida, revealed that Pangola grass was equal to Coastal Bermuda grass in beef production and nutritive value (Blaser *et al.*, 1946). In south Florida it has produced more beef than any other grass tested (Hodges *). In replicated plots, clipped to simulate grazing, it has produced about as much dry matter per acre as Coastal Bermuda (Burton *). It is quite susceptible to frost injury, being killed to the ground by temperatures that would not injure Pensacola Bahia grass or Coastal Bermuda. Some reports indicate that legumes will not grow as well in association with Pangola grass as in association with some other species, such as Dallis grass and Coastal Bermuda. Pangola grass will make good quality grass hay if fertilized and cut every four to six weeks. Little is known concerning the nutritional requirements of this grass other than the observation that it responds well to fertilizer and is particularly sensitive to copper deficiency (Hodges *).

*d. Breeding.* The complete sterility of Pangola grass suggests that it may be a species hybrid of rather recent origin. Attempts to improve it by selection and hybridization have failed due to its sterility (Burton *).

### 12. *Pearl Millet*

*a. Origin and History.* Pearl millet, *Pennisetum glaucum* (L.) R.Br., has been cultivated since prehistoric times, its wild prototype being unknown (Ball, 1903). It is widely grown in Africa and India for human food. In India, where it is grown most extensively under the name of Bajri, approximately 16,000,000 acres are planted annually (Godbole, 1927). It is grown there because the rainfall is too short or the soils are too poor to grow a good crop of grain sorghum. In such regions the seed is the basic cereal and is ground and baked into unleavened bread by large classes of the people. The stover left from the harvest is generally used as livestock feed. Among many African tribes it is used as a famine crop, being planted when corn or the other millets fail.

Pearl millet was probably first introduced into the United States around 1850 (Ball, 1903). Under the names of pencilaria and Mand's forage plant the seed sold at the beginning of the present century for over a dollar per pound. In the South, where it is commonly called cattail millet, the seeds now sell for 10 to 20 cents per pound.

*b. Description.* Pearl Millet is a robust annual bunch grass. Its stems that reach a height of 6 to 10 ft. when mature range from ⅜ to ¾ in. in diameter at the base. Its leaves are more than an inch wide and 2 to 3 ft. long. Its "pearl-like" seeds are borne in large terminal "cattail-like" spikes that range from 6 to 36 in. in length, depending upon the variety. Pearl millet is propagated entirely from seed and is usually planted in 30- to 42-in. rows at rates of 5 to 10 lb. per acre.

*c. Adaptation and Use.* Pearl millet is a warm-season annual that may be grown wherever summer temperatures are reasonably high and rainfall is moderate to heavy. In the summer of 1949 it was grown at a number of locations in Pennsylvania (Fortman *et al.*, 1950) and produced more dry matter than Sudan grass. Ralph Singleton * reported that it made excellent growth on Long Island in 1949, but in the cool summer of 1950 it did very poorly. Although it could probably be grown throughout the South, very few acres have been planted outside of the Coastal Plain. Its ability to make good growth on relatively poor but well-drained sandy soils, probably explains why it has largely replaced Sudan grass in the Coastal Plain. It will often produce more than twice as much dry matter as Sudan grass in this area (Burton *). In the Coastal Plain it is used almost entirely as an annual grazing crop for cattle and hogs, and tests to date indicate that it is the best of the available annual crops for this purpose (Stephens, 1942). Dairymen generally agree that it is superior to permanent pastures for milk production. Proper management is essential if good results are to be had from pearl millet. Grazing rotationally when it is about 18 in. high is required for maximum returns. Mowing to keep the grass from heading out extends the grazing season and improves the quality of the herbage.

Although pearl millet will grow on poor soils, it responds well to fertilizer applications. In 1950 Burton and DeVane * applied 0, 32, 64, and 128 lb. of nitrogen at planting time to pearl millet (growing on a Tifton sandy loam fertilized with 500 lb. per acre of 0-15-15) and obtained yields of 11,360, 22,090, 30,780, and 41,380 lb. of green forage per acre. They also found that these rates of nitrogen applied to Starr pearl millet planted in 19-in. rows gave seed yields of 417, 711, 864, and 1,181 lb. per acre.

Pearl millet is too hard to cure to make a good hay crop in the humid South. It has been used for silage in a limited way, but nothing is known concerning the feeding value of the silage produced.

*Sclerotium rolfsii, Helminthosporium* sp., and *Gloeocercospora* sp. have been found on pearl millet as the seeds begin to mature. These diseases do not seem to attack millet in the younger stages when it is being consumed by livestock. Army worms and lesser cornstalk borers sometimes attack young pearl millet, particularly late plantings, and may kill so many plants that replanting will be required.

*d. Breeding.* Pearl millet is a diploid $2n = 14$ (Karper and Chisholm, 1936). Its protogynous flowering habit (stigmas are exserted several days before the anthers) greatly facilitates natural and artificial cross pollination. Anthers are exserted (first from the bisexual flowers and 24 to 36 hours later from the male florets) every hour of the day and night (Ayyanger *et al.*, 1933). In Georgia the greatest flush of anthesis and pollen shedding occurs over a two-hour period around sunrise (Burton *). Pearl millet is an extremely variable species. Burton * has found that selfing by enclosing the heads in bags invariably results in a loss of vigor. Self-fertility is reduced in varying degrees to the extent that some lines may be highly self-fertile, whereas others are completely self-sterile. Complete self-sterility is usually associated with the development of anthers that fail to produce and shed pollen. Controlled hybrids can be easily made by dusting pollen from the male parent on bagged heads after the stigmas are exserted but before the anthers appear. Using a semitransparent glassine bag permits a check on the condition of the ''female'' head without removing the bag. In some lines the upper half of the head must be cut off before bagging so that all the stigmas will be exserted before the anthers appear. Burton * has found that inbred lines of pearl millet may be handled in much the same manner as inbred lines of corn and that some of the best single crosses may yield more than 50 per cent more forage than common pearl millet. Good inbred lines of millet produce less seed than open-pollinated millet but could be used for commercial seed production. A mechanical mixture of four self-fertile inbred lines planted in a seed production block should give rise to 75 per cent hybrid seed and 25 per cent selfed or sibbed seed. Burton (1948d) has shown that such mixtures yield as much as pure hybrid seed if planted in the usual manner. Thus the release of highly productive pearl millet hybrids rests on the development of good inbred lines and much of the millet breeding at Tifton, Georgia, is directed toward this end. Inbred lines may also be recombined to develop a synthetic variety. Starr millet, developed at the Georgia Coastal Plain Experiment Station, is such a variety. It differs from common pearl millet in being shorter, leafier, later (longer grazing season), easier to manage, and more productive. It produces a higher yield of leaves and in a preliminary grazing study produced 50 lb. more beef per acre. It is the first pearl millet variety to be released in the United States. A number of varieties have been developed for grain production in India (Godbole, 1927), largely through mass selection. Many of these varieties have been introduced, but none of them is well suited for forage production in the South. They are furnishing, however, an excellent source of genes for the pearl millet breeding program.

### *13. St. Augustine Grass*

*a. Origin and History.* St. Augustine grass, *Stenotaphrum secundatum* (Walt.) Kuntze, may be found growing wild throughout the West Indies and is generally considered a native of that region. It also occurs in a wild state in the tropics of Africa, Mexico, Australia, and the Hawaiian Islands. Its ability to withstand close grazing enables it to come in to closely grazed areas and probably explains why it is called sheep grass in British Guiana. It is widely distributed throughout the deep South where it is used almost exclusively for lawns.

*b. Description.* St. Augustine grass is a low-growing perennial that spreads by aboveground stolons. The folded leaves, 2 to 6 in. long, make a dense cover in well-managed lawns. Its seeds are partially embedded in erect fleshy spikes that seldom exceed 8 in. in height. It is propagated by planting sprigs.

*c. Adaptation and Use.* Susceptibility to winterkilling restricts St. Augustine grass to the region south of a line drawn through Augusta and Birmingham. It requires abundant moisture but does not do well on poorly drained soils. Heavy fertilization with nitrogen-carrying materials is required where attempts are made to grow it on poor soils. It is one of the most shade-tolerant grasses and makes an excellent lawn in rather heavy shade, provided its needs for moisture and plant food are met. Burton and Robinson * have found that St. Augustine grass makes its best growth at pH 6 to 7. Liming soils having a pH of 4 to 5 will favor the establishment and growth of this grass.

The chinch bug, a tiny sucking insect that kills St. Augustine grass if allowed to work undisturbed, can be successfully controlled by dusting the affected areas with chlordane dust. Eternal vigilance and early treatment are required if the lawn is to be protected from this insect. Chinch bugs like the warm sunshine and seldom damage St. Augustine grass that is growing in the shade.

Brown patch, a fungus disease, also kills out St. Augustine grass during warm muggy weather. Overwatering may cause the disease to develop. The disease is controlled rather easily by correcting watering practices, stimulating the growth of the grass with fertilizer applications, and using calomel or corrosive sublimate in severe cases.

St. Augustine grass has been used to a limited extent in the muck lands of Florida as a pasture grass. Since it is inferior to other grasses such as Pangola on the sandy soils, future plantings for pasture will probably be restricted to muck soils.

*d. Breeding.* No organized attempt has been made to improve St. Augustine grass by breeding. A blue-green introduction called ''bitter blue'' has been reported to be chinch bug resistant. Dr. Roy A. Bair at Belle Glade, Florida, reports that it withstands chinch bug attacks not because it is more resistant, but because it is more vigorous and is better able to tolerate the insect damage.

### *14. Sudan Grass*

*a. Origin and History.* Believing that somewhere in the world there existed an annual form of Johnson grass, C. V. Piper planned and directed a systematic search for it. Finally in 1909 after making numerous inquiries he found the grass he had long visualized on an African military hay farm. First found near Khartoum in eastern Sudan, the new species was named Sudan grass, *Sorghum sudanense* (Piper) Stapf. Sometime after its introduction into the United States, it was learned that it had been carried into the Sudan region from Egypt. More recently Sudan-like sorghums have been found in northwest and southwest Africa, in Java, and in India. Sudan grass soon found a place in the forage program in every section of the United States. It became an important supplementary summer pasture crop over a wide area. In the dryer sections of the country, many farmers used it as a hay plant. The development of better permanent pastures has reduced the acreage of Sudan grass, but it still holds an important position among the forage grasses in the United States.

*b. Description.* Sudan grass is an annual bunch grass reaching a height of 4 to 8 ft. when mature. Its leaves, approximately 1 in. wide and 2 ft. long, are borne on many stems that seldom exceed the diameter of a lead pencil. The Sudan grass seeds that remain enclosed in the glumes after threshing are produced in a loose open panicle. Sudan grass is propagated entirely by planting seed.

*c. Adaptation and Use.* Sudan grass seed will not germinate well until the soil becomes warm (about two weeks after corn planting time). Like other plants of tropical origin, Sudan grass requires warm to hot weather for satisfactory growth. Its drought resistance enables it to endure periods of drought and still produce fair crops in the low rainfall regions of the Great Plains. Sudan grass is not a poor land plant. It makes its best growth on the heavier soils that are well supplied with plant food, particularly nitrogen and phosphorous. Good drainage is essential. Although Sudan grass contains the prussic acid glucoside, cases of prussic acid poisoning are almost unknown in the region considered in this report. Sudan grass is used largely as a supplementary grazing crop on the heavier soils in the South. There is reason to believe that it should enjoy a wider use for this purpose, since it is generally recognized as one of the most palatable and nutritious grasses that can be grown.

Sudan grass may be used as a soiling crop, but is of minor value for silage. It makes hay comparable to Johnson grass in feeding value. A mixture of Sudan grass and cowpeas or soybeans makes a higher quality hay than Sudan grass alone and is to be recommended where Sudan grass is grown for hay. Sudan grass and the mixtures mentioned above are difficult to cure in the humid South and will probably never enjoy a very wide use for hay production.

*d. Breeding.* Sudan grass is a diploid $2n = 20$ (Katterman, 1930). The variability exhibited by spaced Sudan grass plants would suggest that it reproduces sexually with considerable cross pollination. At Madison, Wisconsin, 6.7 ± 2.29 per cent of natural crossing was observed in Sudan grass (Hogg and Ahlgren, 1943). Garber and Atwood (1945) obtained highly significant differences between strains and years in the amount of crossing in Sudan grass at State College, Pennsylvania. In 1941, 1942, and 1943 they obtained approximately 75, 18.2, and 34.4 per cent of natural crossing in Sudan. Variations in experimental design could have been responsible for some of the seasonal differences observed. They also reported that Karper and Quinby found 31 per cent of natural crossing in one test and 46 per cent in another test located in Texas. Burton * observed 20 per cent of natural crossing in a preliminary test conducted at Tifton, Georgia.

Inbreeding usually results in loss of vigor in naturally cross-pollinated species and apparently Sudan grass is no exception. Although Robertson reported no apparent loss of vigor after three generations of inbreeding in Sudan grass, Wenholz found a loss of vigor in some lines (Vinall and Hein, 1937). Burton * grew 23 self- and open-pollinated progenies of selected plants side by side in 1937 and observed that the first generation of inbreeding resulted in a noticeable reduction in vigor in most instances. Yield tests at Madison, Wisconsin (Hogg and Ahlgren, 1943), showed that a loss in vigor and seed yield accompanies inbreeding.

On the basis of these tests, Hogg and Ahlgren (1943) concluded that "it may be possible to select inbred lines which are as vigorous as the parent stock even though the majority of the lines are inferior in yield."

Resistance to the foliage diseases, lower prussic acid content, and sweetness have been the major objectives of the Sudan grass breeders. Tift Sudan was developed by crossing common Sudan grass with the disease-resistant Leoti sorghum, backcrossing the most resistant plants in 35,000 $F_2$ progeny to Sudan grass, and selecting the most resistant fine-stemmed individual in 30,000 $F_2$ progeny from this backcross. This selected plant bred true for disease resistance when selfed and was increased to give rise to Tift Sudan (Burton, 1943c). This variety is much more resistant to the foliage diseases than other Sudan grass varieties, making it superior in the humid South where these diseases are prevalent. It is not sweet, it contains more prussic acid than common Sudan, it starts off more slowly than common Sudan, and does not produce as much seed. In spite of its faults, it is still the best variety for the humid South and should be used until superior varieties can be developed.

Karper and Quinby * developed sweet Sudan by crossing Leoti sorghum and common Sudan. Sweet Sudan released on a large scale in 1944 had many desirable characteristics. It was sweet and more palatable, particularly in advanced stages of growth than any other Sudan. It carried resistance to chinch bugs, charcoal rot, and some resistance to some of the foliage diseases. It possessed a uniform sienna seed coat and produced more seed per acre than common Sudan. Although it is widely planted, it possesses some of the same faults as Tift Sudan, namely, higher prussic acid content and slower starting than common Sudan. Greater disease resistance must be incorporated in sweet Sudan, however, before it will be well adapted to the humid South.

The Wisconsin workers (Hogg and Ahlgren, 1943) have concentrated on the development of a low prussic acid Sudan grass and have made progress. D. C. Smith, H. L. Ahlgren, and J. M. Sund * report that Wisconsin 797 developed from a double cross involving Tift Sudan and lines from Texas and Kansas is being released under the name of Piper. Sudan grass. This variety is quite variable in seed and plant color but appears to be relatively homogeneous for its major economic characters. They list the following characters for this variety: Increased forage yield, resistance to important diseases (less than Tift Sudan), low level of cyanogenetic glucoside production, average to slightly coarse growth, improved seed yields, improved seed character, and better stiffness of stalks when mature.

### 15. *Tall Fescue*

*a. History and Origin.* Tall fescue, *Festuca arundinacea* Schreb., can be found growing in damp, wet places in Europe, Africa, and North America. Europe, however, is generally considered its center of origin. The date when tall fescue was first introduced into the United States is not known. There is good reason to believe, however, that it first came as a mixture in grass seed brought to this country by early European immigrants. It is only within the past 15 years that this grass has assumed any economic importance. During this period it has become one of the most popular pasture grasses in the upper south.

*b. Description.* Tall fescue is a perennial bunch grass that reaches a height of 2 to 4 ft. when mature. Its dark green basal leaves give the grass a tufted appearance when growing in thin stands. Although it has neither rhizomes nor stolons, the diameter of the plant slowly increases with age until old stands develop a uniform sod. Its seeds are borne in many flowered lanceolate spikelets in panicles that may reach 12 in. in length. Tall fescue is propagated from seed.

*c. Adaptation and Use.* Few grasses are adapted to such a wide range of soil and climatic conditions as tall fescue. It can be grown farther south than any of the common cool-season grasses and will also survive the winter in most of the northern states. Although it grows on wetter soils than the common cool-season grasses, it also has more drought resistance than most of them. Tall fescue is probably best adapted to the soils and climate found in the upper south. There it will grow and survive on soils too poor to maintain such grasses as Kentucky bluegrass and bromegrass. Farther south, particularly in the Coastal Plain, tall fescue succeeds only on soils that are rich, wet, or preferably both. Burton * has found that tall fescue becomes dormant and dies out the first summer on a sandy loam of only moderate fertility at Tifton, Georgia. If given 320 lb. of nitrogen per acre per year in split applications on the same soil, it maintains a perfect stand, remains green, and even makes some growth throughout the summer. It is doubtful, however, if the returns would justify such a fertilization practice.

Orien Brooks * has observed at Blairsville, Georgia, that tall fescue will tolerate more frost and supply more winter grazing than orchard grass, remaining in good grazing condition through zero temperatures. When grown in association with ladino clover, it has made an excellent pasture combination for the mountains of Georgia. Chamblee (1950) and other workers have observed that tall fescue suppresses the growth of ladino clover more than orchard grass. Seeding less tall fescue (5 to 6 lb. per acre) with ladino clover has offered a partial solution to this problem. It is generally recognized that tall fescue is less palatable than most of the cool-season grasses such as bromegrass, orchard grass, and timothy. When grown in association with a legume such as ladino clover, however, it is readily grazed, and the animals grazing the mixture consume enough to make excellent gains.

Tall fescue makes good hay, particularly when grown in association with a legume. The surplus growth that develops in fescue-ladino clover pastures in the early summer is often mowed and saved for hay.

Tall fescue has considerable value as a turf grass for roadsides, airfields, and athletic fields in the upper South. It is too coarse to make a high quality lawn but under some circumstances has made a more satisfactory cover than other lawn grasses previously used. It will not tolerate frequent mowing in the Coastal Plain and, so far as the writer is aware, has never survived a complete summer season under lawn management in this area.

*d. Breeding.* Tall fescue is a hexaploid $2n = 42$ (Litardiere, 1923). Beddows (1931) found that tall fescue plants produced 5.1 times more seed when open-pollinated than when selfed. He reported, however, that it was not as self-sterile as meadow fescue. The self-sterility in tall fescue observed by a number of American workers and the variation exhibited by spaced progenies of this grass indicate that it is cross pollinated and reproduces sexually.

Two varieties of tall fescue are being widely grown today. Alta fescue, selected by Schoth * in Oregon for increase in 1932, appears to be similar to Kentucky 31. The latter variety was found in 1931 growing on a farm in Menifee County, Kentucky, where it had been growing for over 50 years. It was tested for several years and was increased for general distribution around 1940. The phenomenal spread of this grass is shown by the estimated 7,000,000 lb. of seed of Kentucky fescue produced in 1950. Dr. E. N. Fergus * of Lexington, Kentucky, who played the leading role in the evaluation and release of Kentucky fescue reports that attempts to improve it by breeding have met with comparatively little success to date. Greater resistance to *Rhizoctonia* and *Helminthosporium* net blotch, greater palatability, and greater summer tolerance are some of the main objectives of the breeders working with this grass.

### *16. Vasey Grass*

*a. Origin and History.* Vasey grass, *Paspalum urvillei* Steud., probably originated in the Argentina-Uruguay region of South America. It was found growing wild around New Orleans in 1882, indicating that it was introduced before that time. Its wide distribution along highways and railroad tracks throughout the South suggests that it was accidentally introduced early in the history of this country.

*b. Description.* Vasey grass is an erect bunch grass that reaches a height of 2 to 6 ft. when mature. It produces a few basal leaves, but most of the leaves arise from nodes on the erect stems. The hairy seeds of Vasey grass are borne on racemes 10 to 25 of which occur in a single inflorescence. It seeds profusely throughout the summer, but the seeds shatter as soon as they are ripe, making it difficult to harvest much seed at any one time. Vasey grass is propagated by seed.

*c. Adaptation and Use.* Vasey grass is well adapted to the Carolinas and the Gulf States. It is one of the few grasses that will grow and do well in standing water. It also occurs in dry sites, indicating that it has considerable drought resistance. It tolerates more frost than most warm-season grasses and may furnish a little grazing in mild winters in the lower South. It responds to fertilization but will make much better growth on poor soils than Dallis grass. The difficulties associated with the harvesting and planting of the hairy seed help to explain why few acres have been planted to this grass. Where it has taken over areas on its own, it has been utilized for both pasture and hay. Cattle find Vasey grass very palatable and soon kill it out by overgrazing unless it is grazed rotationally. On a sandy soil at Ona, Florida, Vasey grass produced as much beef as Coastal Bermuda and among the grasses tested was exceeded only by Suwannee Bermuda and Pangola grass (Hodges *). If cut at an early stage, Vasey grass makes a palatable hay of good quality. It is highly resistant to ergot and the foliage diseases that attack Dallis grass. There is good reason to believe that Vasey grass may enjoy a more important place in the southern forage and pasture program of the future, particularly on some of the wet lands in this region.

*d. Breeding.* Vasey grass is a tetraploid having 40 chromosomes as the $2n$ number (Burton, 1940a). In 1938 and 1939 Burton * space-planted 3,200 Vasey grass plants from selfed seed and 5,000 plants from open-pollinated seed hoping to find either decumbent or prostrate individuals that might more successfully withstand close grazing. No such plants were found, and the entire population showed a remarkable degree of uniformity in type. This uniformity suggested that apomixis might be the predominant method of reproduction in this species. Five hybrids between Vasey grass and *P. malacophyllum* Trin. ($2n = 40$) carried 40 chromosomes as the $2n$ number (Burton, 1943c). Had apomixis been the sole method of reproduction in this grass, these hybrids would have had at least 60 somatic chromosomes (40 from Vasey grass plus 20 from *P. malacophyllum*). Regardless of what the method of reproduction may be, the possibilities of improving Vasey grass by selection do not seem good on the basis of experience accumulated to date.

### *17. Zoysia Grass*

*a. Origin and History.* The Zoysia grasses of which there are now three species in the United States originated in southeastern Asia. *Zoysia tenuifolia* Willd., commonly called Mascarene is of little importance. Japanese lawn grass, *Zoysia japonica* Steud., and Manila grass, *Zoysia matrella*, are becoming increasingly popular as lawn grasses in much of the United States.

*b. Description.* The Zoysias are low-growing rhizomatous perennials. Their short leaves are very tough, making them unsuited for grazing purposes. Japanese lawn grass has wider leaves and is coarser than Manila grass. Both grasses make a very dense turf. Their seeds are borne on short erect spikes that seldom reach a height of more than 8 in. The lack of commercial sources of seed has made it necessary to propagate the Zoysia grasses vegetatively.

*c. Adaptation and Use.* Japanese lawn grass may be successfully grown as far north as Boston, whereas about 40 degrees latitude is the northern limit of adaptation for Manila grass. *Zoysia matrella* (L.) Merr., the species generally used in the South, is one of the earliest grasses to begin growth in the spring and is one of the last to turn brown in the fall. It remains green nine to ten months in Central Alabama (Sturkie and Fisher, 1942). Although it makes its best growth on heavy soils, good turf can be established on the sandy soils if plenty of plant food is used. Zoysia is less drought resistant than Bermuda grass and will require more watering during dry periods to maintain a green turf. Sturkie and Fisher (1942) report that it has stood more shade than any of the common summer-growing turf grasses. They also found that it dies when the pH of the soil became as acid at 4.5. Its two major faults are its slow rate of spread and the lack of a commercial source of seed. At Auburn, Alabama, 2-in. plugs of Zoysia sod set 12 in. apart required two years to establish a sod. In spite of these faults, it makes such an excellent wear-resistant turf once established that many people are willing to spend the extra time and money required to establish a lawn of this grass.

*d. Breeding.* Forbes* working at Beltsville, Maryland, has found Zoysia japonica to be a highly variable species. Variations in coarseness, rate of spread, frost resistance, and seed production have been observed, indicating that superior varieties capable of reproduction by seed should be available soon.

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# Chemical Treatment of the Soil for Nematode Control

A. L. TAYLOR
*U.S. Department of Agriculture, Beltsville, Maryland*

CONTENTS

*Page*
I. Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . 243
  1. General . . . . . . . . . . . . . . . . . . . . . . . . . . 243
  2. Historical . . . . . . . . . . . . . . . . . . . . . . . . . 246
II. The Practice of Soil Fumigation . . . . . . . . . . . . . . . . 248
  1. Basic Principles . . . . . . . . . . . . . . . . . . . . . . 248
  2. Materials . . . . . . . . . . . . . . . . . . . . . . . . . 251
  3. Precautions . . . . . . . . . . . . . . . . . . . . . . . . 253
  4. Methods . . . . . . . . . . . . . . . . . . . . . . . . . . 253
  5. Soil Factors . . . . . . . . . . . . . . . . . . . . . . . . 255
III. The Effects of Soil Fumigation . . . . . . . . . . . . . . . . 256
  1. Effectiveness . . . . . . . . . . . . . . . . . . . . . . . 256
  2. Economics . . . . . . . . . . . . . . . . . . . . . . . . . 259
  3. Determination of Practicability . . . . . . . . . . . . . . . 260
  4. Future Prospects . . . . . . . . . . . . . . . . . . . . . . 261
IV. Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . 261
  References . . . . . . . . . . . . . . . . . . . . . . . . . . 263

## I. Introduction

### 1. General

Among the many factors which influence the productivity of soil used for the growing of crops, those due to the presence of soil-inhabiting organisms have long been recognized as highly important. As Russell (1915, 1920) has pointed out, living organisms occur in the soil in enormous numbers and numerous forms, ranging in size from very small bacteria to comparatively large insects and earthworms. All these in the final analysis, depend for food on plants growing in the soil. Saprophytic forms of soil organisms utilize for this purpose the dead remains of plants and, from the standpoint of the grower of crops, are beneficial, since continuing use of the soil would be impossible if they were not present. But a large variety of organisms living in the soil feed on living plants as parasites, diverting some of the nutrients which might otherwise be utilized by the plants to their own use, and often by their feeding causing distortion, rotting or other pathological changes in the plant tissue. In soil which is not cultivated, the soil organisms arrive at some sort of balance with each other and their environment. When the soil is cultivated, all the procedures necessary in practical crop production change the environment and interfere with this balance to some degree, often to the advantage of the parasitic organisms. This is especially true where the soil is used for the growing of the same crop year after year, since ideal conditions are provided for the multiplication of parasitic organisms particularly adapted to feed on that crop as a host plant. It is also true to a smaller, but still important, extent where crop rotation is practiced.

The usually gradual diminution of crop yields caused by increases in the parasitic components of the soil biotic complex have been known for many years, but the cause has only recently begun to be well understood. In this country we speak of ''worn out'' soil, and in other countries soil which is unproductive is said to be ''sick'' or ''tired,'' often qualified as ''oat-sick soil,'' ''alfalfa-sick soil,'' ''soil tired of beets,'' and the like. In some cases, the mineral elements necessary for plant growth have been exhausted from such soils, but in other cases the cause has repeatedly been found to be the accumulation of soil-inhabiting parasites. Our ancestors could solve the problem by moving on to virgin soil. Today crop rotation is used and is effective if the rotation crops are not attacked by the same parasites. Greenhouse owners know that it pays to change their soil at intervals, or to sterilize it by steam or other methods. The factor common to all these practices is that they eliminate or greatly reduce the crop damage caused by soil parasites (Steiner, 1949a,b).

Soil-inhabiting parasites are of many kinds, but the discussion in this paper will be mainly confined to one widespread and numerous class, the plant parasitic nematodes. Of these, perhaps the best known are the root-knot nematodes of the genus *Meloidogyne,* formerly considered a part of the genus *Heterodera.* The latter genus now includes only the cyst-forming nematodes such as the sugar beet nematode and the golden nematode of potatoes (Chitwood, 1949) which are also well-publicized plant parasites. Specialists in the study of plant parasitic nematodes know that several hundred species of other genera are also capable of attacking plants, and consider many of these to be major pests quite as important from the economic standpoint as the root-knot nematodes or the heteroderas (Steiner, 1949a).

Plant parasitic nematodes are most prevalent and do the most damage in the South and other warm regions of the United States, because a long-growing season is favorable to their multiplication. In these regions many species are known to be pests of all crops with cotton, tobacco, peanuts, corn, sweet potatoes, and vegetables being most heavily and generally damaged. Prevalence of nematodes as important pests diminishes toward the north, but they are by no means rare even in the northern states. Root knot is common on vegetables in New York State, and tobacco in the Connecticut Valley is often severely damaged by nematodes. Many of the sugar beet growing regions of the country are infested with the sugar beet nematode, and the golden nematode of potatoes is found on Long Island.

Nematodes attack not only the roots and other underground parts of plants such as tubers and corms, but also attack the above ground parts, including stems, leaves, and flowers. Nor are their attacks confined to annual plants. Perennials, including citrus, peach, and fig trees are often damaged. Nematodes are found wholly or partially embedded in the living plant tissue, or may be ectoparasites, feeding on the plant but not entering it. Some are sedentary, never moving after they have entered the plant and started to develop. Others wander through the plant tissue or over the surface. Some are known to attack only a few species of plants, and others attack a wide variety of plant species (Steiner, 1949a).

In general, it may be said that nematodes feed on all crop plants and that plant parasitic nematodes can be found in all soils. In any given case, it is only a question of what species are present, and how many are present, or from the standpoint of the practical grower, whether or not they are causing enough damage to make it worth while to initiate control measures.

When soil is heavily infested with plant parasitic nematodes, any considerable reduction in their numbers will result in improved plant growth, particularly if this can be done without at the same time interfering too seriously with the activities of the beneficial components of the soil flora and fauna. Fortunately, this can be accomplished by partial sterilization of the soil, by the use of either heat or chemicals. Apparently plant parasitic nematodes are more easily killed than saprophytic fungi or bacteria, and even if some of the saprophytic organisms are killed, there is no obstacle to the rapid multiplication of those remaining, once the soil has cooled or the chemical has dissipated or decomposed. Their food supply still exists, and they are capable of rapid multiplication. But plant parasitic nematodes can multiply only when they have a host plant on which to feed, and their rate of multiplication is much lower than that of saprophytic microorganisms, the life cycle of most species being a matter of days or weeks, instead of hours. If enough of the nematode population is eliminated before the crop is planted, plants can be grown to harvest before they are attacked by sufficient numbers to cause damage.

Experimental and commercial applications of soil fumigants for nematode control have shown that yield increases of sufficient magnitude to make their use economically practical can be obtained with many crops in a wide variety of locations. Such trials have also indicated that nematodes are an important factor in crop production in many parts of the United States where they were not previously considered to be so. Yield data from a surprisingly large percentage of trials have shown increases of more than 20 per cent, even when trial plots were selected with no previous knowledge of the nematode populations present.

As will be explained, soil fumigation has its limitations, but is nevertheless of considerable value. It is of more than ordinary interest, because it extends chemical plant pest protection to the subterranean portions of plants and is in its way as great a step forward today as were sprays and dusts for protection of the above-ground portions of the plants in past years.

## 2. *Historical*

Almost as soon as soil-inhabiting nematodes were recognized as plant parasites, attempts were made to kill them by means of chemicals. A long list of likely and unlikely substances which have been tested for this purpose can be assembled from the literature. Only those now in general use, together with a few promising new materials will be discussed here.

Kühn (1881) used carbon bisulfide to kill sugar beet nematodes, though without conspicuous success. Carbon bisulfide was tested by Bessey (1911) against root-knot nematodes and was reported to be "undoubtedly the most efficient chemical for destruction of the nematode in the field." He applied it by pouring measured amounts into holes punched in the soil, evidently following methods developed in France, where it had been extensively used for control of *Phylloxera*.

Matthews (1919, 1920) reported excellent control of root-knot nematodes in pot and field experiments with chloropicrin. G.H.G. (1928) reported killing of larvae of root-knot nematodes in the laboratory with chloropicrin, and referred to a newspaper article concerning field experiments conducted by Maxwell Johnson in California. Johnson (1934) applied for a patent on "a method of fumigating soil" in 1929, specifying "liberating chloropicrin beneath the surface of the soil and retarding the upward escape of vapors by means of an impervious covering laid on the surface." Johnson and Godfrey (1932) reported considerable development of methods for using chloropicrin, striking reductions in root-knot infection and increases of growth and yield of pineapples in Hawaiian fields. Godfrey (1935) continued this work and reported that the use of chloropicrin had been shown to be economically feasible in heavily infested pineapple fields. Stark (1938) suggested the possibility of confining the vapors of chloropicrin by sprinkling the soil surface with water instead of by using a paper or other cover.

Commercial development of soil fumigation began in 1937 with the entry of Innis, Speiden and Company into the field, introducing the use of chloropicrin to operators of greenhouses as a substitute for or a supplement to the more expensive control of soil pests by steaming. Chitwood (1939) developed methods of determining dispersion of soil fumigants under field conditions, and Taylor (1939) published mathematical tables for calculating optimum applications. Taylor and McBeth (1941b) developed the "spot" method of fumigating soil to be used for crops planted in widely spaced hills and suggested that fumigation of rows would be a logical extension of the method.

Methyl bromide was first reported as a soil fumigant for control of nematodes by Taylor and McBeth (1940). They also devised a method of applying the gas under a paper cover (1941), and reported that 10 per cent mixtures of methyl bromide with liquids of higher boiling point were effective against nematodes when applied as liquids (1942). Stark, Lear, and Newhall (1944) reported good control of root knot with a solution of 10 per cent methyl bromide in a mixture of three parts of ethylene dichloride and one part of carbon tetrachloride produced by the Dow Chemical Company, which had also become active in the selling of soil fumigants.

Up to this time, the use of soil fumigants had been confined to crops of high value because of the cost of the chemicals. The report of Carter (1943) that a crude mixture of dichloropropene and dichloropropane obtained from the Shell Development Company was a very good nematocide and much cheaper than those then in use opened the way for a vast new development. Large-scale use of this product in the pineapple fields of Hawaii and vegetable fields in California followed immediately.

In January, 1945, a second fumigant of low cost, ethylene dibromide, was reported by Christie as having given excellent results in preliminary experiments. Ethylene dibromide had also been under test on a field scale near Seal Beach, California, by the Dow Chemical Company, and further field scale tests were made in various locations in 1945. Results of some of these were reported by Thorne and Jensen (1946). Rapid commercial development of ethylene dibromide began in 1946.

Christie (1947) reported promising preliminary tests with ethylene chlorobromide and allyl bromide. Lear (1950) described the efficacy of dichlorobutene against the golden nematode of potato and root-knot nematodes. Kreutzer and Montagne (1950) reported that chlorobromopropene is an excellent soil fumigant. A subsequent newspaper report indicates that chlorobromopropene is now in the early stages of commercial development by the Shell Chemical Corporation (New York Times, September 17, 1950).

Development of machinery for the application of soil fumigants has followed the progress of the fumigants themselves, but little of it has been reported in the literature, having been the work of mechanics, farmers, and representatives of the companies selling soil fumigants. Hasson (1920) devised an applicator which delivered chloropicrin in front of a plow and used an air pump to force the liquid from the supply tank. Neller and Allison (1935) described an applicator mounted on a small garden tractor which delivered the fumigant through tubes attached to the rear of shanks. Taylor (1939) was granted a public patent for a hand applicator which delivered the fumigant through a tube thrust into the soil and had a pump with adjustable stroke for metering. These principles are still in general use, but many subsequent improvements have been made in details.

Procedures as new and novel as soil fumigation cannot be considered successful until they have been popularized and the materials are readily available to prospective users. A considerable amount of time, money, and effort has gone into such educational activity in the past few years on the part of research workers, Extension Service personnel, and company representatives. The importance of these activities cannot be overestimated.

In addition to the fumigants mentioned above, various solids are used to some extent for nematode control, principally in tobacco and other seed beds. The most popular of these is urea (Clayton *et al.*, 1945). Nitrites, particularly those of calcium and potassium, and sodium azide have also been reported as giving good nematode control (Clayton *et al.*, 1949).

## II. The Practice of Soil Fumigation

### 1. *Basic Principles*

Efficient use of soil fumigants involves consideration of a number of factors, the most important of these being the nature and habits of the plant parasitic nematodes, the soil in which they live, the physical and chemical properties of fumigants, and the machinery available for application.

The nematodes which most concern the practical grower are to be found in the soil during all or part of their lives. All are comparatively small, ranging from about 0.25 mm. to 5.0 mm. in length, with most being less than 2.0 mm. long. While in the soil, they are more or less slender worms and are able to move through the interspaces between particles, though this ability is limited by their small size. Taylor and McBeth (1939) found that the maximum active migration of larvae of the root-knot nematode was about 1 ft. per month in a straight line. It should be emphasized that this was the maximum and that the average was probably less than half this distance. There was no evidence of attraction to plant roots as little as 6 or 8 in. away, the few individuals reaching these plants apparently arriving more or less by chance during random movements in the soil. It is known that some nematodes are attracted by a substance emanating from roots, but apparently this is effective only at very short distances. In the success of soil fumigation, this limited mobility is important, since it insures that soil locally freed of nematodes will not quickly become reinfested by reason of nematodes migrating from the surrounding soil.

Plant parasitic nematodes reproduce by means of eggs which may be deposited either in the soil or in plant tissue. Eggs of the root-knot nematode and some other species are deposited in a mass of mucoid substance. Most of the eggs of the various species of the genus *Heterodera* are retained within the body of the female, which is transformed into a cyst highly resistant to decay. Larvae of other species, such as the wheat gall nematode, remain for a time in a cyst formed from some plant part. However enclosed, the eggs or larvae are protected to some extent from adverse conditions and from the effects of soil fumigants.

The reproduction rate of nematodes is very low compared with that of fungi and bacteria. The length of the life cycle of one species of root-knot nematode studied by Tyler (1933) varies inversely with the soil temperature up to an optimum, being 25 days at 27°C. and 87 days at 16.5°C. A long life cycle implies that a population greatly reduced will not quickly increase to its former level.

The cuticle of nematodes is relatively impermeable, and the eggs also have an impermeable membrane, both apparently of a lipoidal nature. Furthermore, in moist soil, nematodes and their eggs will ordinarily be surrounded by a thin film of water. These barriers must be penetrated by poisons used to kill them.

The principal protection of the plant parasitic nematodes in the soil is the soil itself. Where annual crops have been grown, nematodes will be distributed through the upper 18 in. of the soil, or even deeper in some cases, and highly effective control can be obtained only by poisons distributed through most of this portion of the soil. While it is possible to mix a powdered solid with the soil, it is very difficult to do so to a depth of more than 8 or 10 in. with the machinery available on the average farm. Aqueous solutions of chemicals will eventually diffuse through the soil, but this is a very slow process compared with the speed of diffusion of gases or vapors.

As Chitwood (1950) has pointed out, fumes or gases liberated in the soil tend to saturate the soil moisture at the point of application before diffusing farther. Best diffusion can be expected when the water solubility of the fumes is low. Soil fumigants now in use have water solubilities in the range of one part in 200 to one part in 3333. If water solubility is too low, however, the film of moisture around the eggs and larvae will not be penetrated.

One chemical, methyl bromide, which is a gas at ordinary soil temperatures is used for soil fumigation, but it is used only on small plots because a gas-tight cover must be used to confine it to the soil. For large-scale use, fumes formed by the evaporation of liquids have considerable practical advantages, not only in ease of application, but also in the properties of the fumes produced.

Liquid soil fumigants must form fumes readily, but not so quickly that they escape from the soil without being dissolved in the soil moisture. On the other hand, if the vapor pressure is too low, there is a tendency for the fumes to be retained in the soil for long periods. Most chemicals which are capable of killing nematodes are also somewhat poisonous to plants and must have diffused out of the soil or be decomposed to harmless forms before the crop is planted.

Optimum economy in the use of soil fumigants is obtained when spacing of applications is adjusted to the characteristics of the fumigant and of the soil in which it is used. In uniform soil, application of a given amount of fumigant will kill nematodes at a certain distance in all directions from the point of application, and this distance tends to approach a maximum which will not be exceeded however much the amount applied is increased. This implies that for any given set of conditions, there is an optimum combination of amount of fumigant per application and spacing of the applications.

Since the fumes tend to diffuse evenly in all directions from the point of application, the shape of the volume of fumigated soil is more or less spherical where the fumigant is applied at a point, or cylindrical where a continuous stream is delivered in the soil. If the fumigant is placed too deep, this effect will leave unfumigated areas at the soil surface between application points, while if the depth is not sufficient, considerable fumigant will be lost at the surface.

Significant crop increases may sometimes be obtained by killing only a small proportion of the nematodes in the field, or it may be necessary to kill a very large proportion. This depends on the nature of the crop, the spacing of the rows or hills, the length of the growing season, the species of nematodes present, and many other factors. The invariable requirement with all crops is that enough nematodes be killed so that the plants are not exposed to heavy infection in the early stages of growth when they are most susceptible to damage. A small number of nematodes may kill a seedling or injure it severely, whereas the same number would produce no appreciable effect on a larger plant.

### 2. *Materials*

Chloropicrin is a liquid which is used at the rate of 200 lb. per acre for nematode control, though two or three times this amount is often applied since fungi, bacteria, and weed seeds in the soil can also be controlled with increased amounts. It lacks conspicuous ability to penetrate undecayed crop residues and to kill the contained nematodes, so results are often poor if it is used too soon after an infected crop has been plowed under. It should not be used in locations where the fumes come in contact with growing plants, since this can cause serious damage. Best results are obtained when the soil temperature is in the range of about 60° to 85°F., minimum temperature for application is 45° to 50°F. on mineral soil or 65°F. on muck soil. A "water seal" formed by sprinkling with enough water to wet the top inch or two of soil, or a cover over the soil to confine the fumes must be used. The soil can be planted in from five to twenty-five days after application, the time necessary for the fumes to diffuse out of the soil being dependent on temperature, moisture, and soil type. Precautions must be used in handling chloropicrin because its fumes cause profuse watering of the eyes when present in the air in low concentrations, and violent coughing, vomiting, or even death in high concentrations. Nevertheless, it is not particularly dangerous to use, since the distinctive odor and watering of the eyes give ample warning of its presence long before the more serious effects ensue. No one will voluntarily remain in even a low concentration of chloropicrin fumes. Gas masks of the proper type provide complete protection. Chloropicrin is shipped in heavy cylinders, or in 1-lb. bottles sealed in cans. It is somewhat corrosive to applicators, but this is not a serious matter if they are properly cleaned after use. There is no fire hazard.

Methyl bromide is available in two forms. One of these is a mixture of 98 per cent methyl bromide and 2 per cent chloropicrin, the latter being included as a warning agent since methyl bromide is odorless. This mixture boils at about 41°F. so can be shipped only in heavy cylinders in bulk, or in 1-lb. cans. It is applied as a gas under a gas-tight cover placed over the soil, a method suitable only for small plots. Other mixtures of methyl bromide contain 10 to 15 per cent of pure methyl bromide mixed with liquids such as xylene or ethylene dichloride and carbon tetrachloride. Nematode control with these mixtures is excellent when they are used at rates of 78 to 100 gallons per acre with a cover or water seal, but there is little effect on fungi and bacteria. Methyl bromide penetrates undecayed roots readily, its fumes have no effect on growing plants in small concentrations, and it escapes from the soil readily. Seeds can be planted two days or transplants set four days after fumigation. These properties make it especially valuable for greenhouse work. The 98 per cent mixture controls weeds when used at the rate of 1 lb. to 100 sq. ft., and will also control fungi and bacteria at higher rates of application. Methyl bromide is not unpleasant or dangerous to handle if precautions are taken to avoid breathing the fumes. The 98 per cent mixture has no fire hazard, and the mixtures present no great danger in this respect.

Ethylene dibromide is a heavy liquid which is sold for soil fumigation purposes in mixtures containing about 10, 20, or 40 per cent by volume, the diluent being naphtha. Good nematode control is obtained on most mineral soils by application of about 15 gallons of the 20 per cent mixture or corresponding amounts of the more dilute or more concentrated material. It is an excellent insecticide, but has little effect on bacteria, fungi, or weed seeds. Penetration of undecayed crop residues is good. The fumes are not toxic to plants exposed to low concentrations in air. It can be applied to soil at temperatures as low as 50°F., and no water seal or cover is necessary. The soil can be planted 14 days after application. Ethylene dibromide fumigants are not disagreeable or dangerous to handle with ordinary precautions. They are inflammable, but not particularly corrosive to applicators. A 55-gallon drum is the usual shipping container.

Dichloropropene is a liquid usually sold in mixtures containing 50 per cent of 1,3-dichloropropene, the balance being mostly dicholoropropane. The minimum application is 20 gallons per acre, at which rate excellent nematode control is obtained in ordinary mineral soils. Muck and peat soils require about twice this amount for comparable control. As an insecticide, it is fairly effective. Heavy applications have been reported as giving some control of fungi and bacteria, but it is not recommended for this purpose. Dichloropropene mixtures have little effect on weed seeds under ordinary conditions of application. Dichloropropene mixtures will damage plants if injected into the soil around their roots, but there appears to be no danger to plants from moderate concentrations in air. These fumigants have a pungent odor, but are not disagreeable or dangerous to handle if ordinary precautions are observed. Applications can be made to soils at temperatures as low as 40°F. At least two weeks are usually allowed for the soil to aerate after planting. Dichloropropene fumigants are corrosive to steel in the presence of moisture, but can be shipped in 55-gallon steel drums or stored for years in these without corrosion, if tightly sealed.

Carbon bisulfide is readily available and can be used as a soil fumigant for nematode control at the rate of 750 to 1,000 lb. per acre. It is not recommended for this purpose because of its extreme fire and explosion hazard.

### 3. *Precautions*

Besides the precautions mentioned above, others should be observed with all soil fumigants. They should be kept from contact with the skin in any way, or if spilled accidentally, should be washed off as quickly as possible. If spilled on clothing, the garment should be removed immediately and not worn again until washed or cleaned. If spilled on shoes, these should be removed instantly and not be used again for several days. No risk should ever be taken of getting fumigant in the mouth or eyes. If fumigants are used indoors, they should always be used with adequate ventilation, and breathing of the fumes for long periods should be carefully avoided.

### 4. *Methods*

Application of a liquid soil fumigant is a matter of placing the liquid beneath the soil surface and covering it immediately with soil. It may be distributed as continuous streams or placed in rows of individual applications as convenient. Large-scale applicators are built to deliver continuous streams, and hand applicators are used to place rows of applications. Spacing is 10 to 12 in. between rows and between individual applications in rows. Depth of application in field work is usually 6 to 7 in.

The typical large-scale applicator is built on an ordinary farm tractor and delivers the fumigants through tubes attached to the rear of 6 to 10 shanks which open narrow furrows in the soil. The shanks are attached to the tractor cultivator to provide means of lowering to working depth and raising clear of the soil. A pump actuated by the tractor power takeoff moves the fumigant from the supply tank to the shank tubes. Metering of the fumigant is effected by placing calibrated orifices in the lines leading to the shanks and adjusting amount of fumigant delivered to tractor speed by varying orifice size or pump pressure. The shanks are followed by a drag to cover the furrows and smooth the soil surface. Machines of this type can apply fumigant to an acre or more in an hour.

Other tractor applicators deliver the fumigant to the bottom of the open furrow ahead of a plow where it is immediately covered with soil turned from the new furrow. Some of these machines have no pump but depend for metering on the pressure produced by gravity flow from a tank mounted high on the tractor.

Shank and plow applicators not mounted directly on the tractor, but attached to it as a trailer, are also popular.

For small-scale fumigation jobs, several methods have been devised. The simplest is to pour the required amount of fumigant evenly along the bottom of an opened furrow and to cover with soil immediately. Alternatively, holes can be punched in the soil and a measured amount of fumigant poured in each by any convenient means. Hand applicators deliver the fumigant through a spike thrust into the soil and use a pump with adjustable stroke for metering. With one of these, a reasonably diligent workman can apply fumigant to about one-fourth of an acre per day.

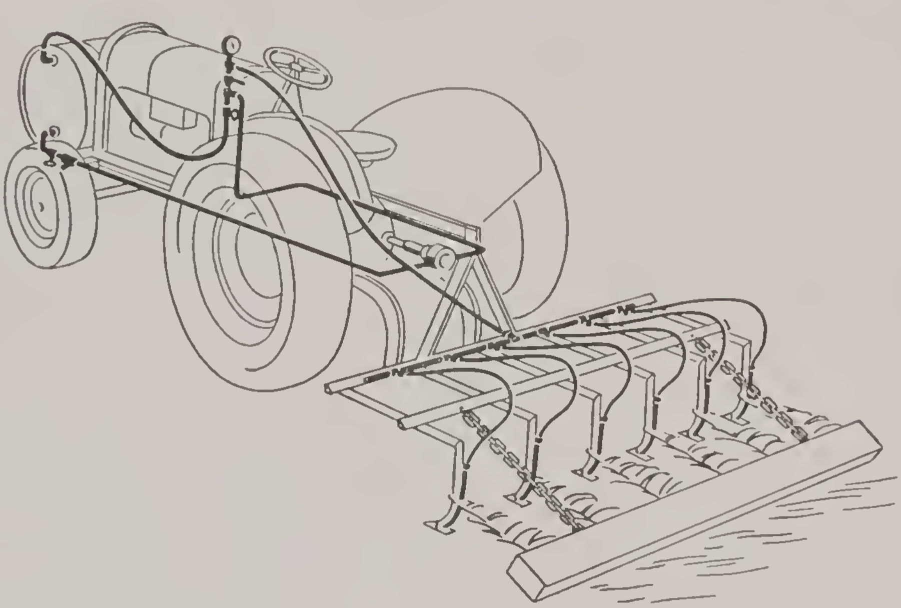

FIG. 1. Diagram of soil fumigant applicator mounted on tractor (Shell Chemical Corporation).

Water-soluble capsules, each containing one-half cubic centimeter of ethylene dibromide, have recently become available. These are simply dropped in holes punched in the soil and covered (Carson, 1950).

Numerous trials of soil fumigants in water solution or as emulsions have been made, but such methods of application have no advantage over the conventional ones except in special circumstances. Fumigants applied as emulsions are often less efficient than corresponding amounts applied without mixing. This is particularly true if they are simply poured on the surface of the soil and not placed beneath it.

Mixtures containing 98 per cent of methyl bromide require a different method of application, since the material is a gas at ordinary temperatures. A gas-tight cover is placed over the soil and supported a few inches above its surface by wires bent in the form of arches or by other means. The edges of the cover are buried to a depth of at least 6 in. at the edges of the plot. The open end of a flexible tube is placed in a shallow container under the cover and the tube is buried in the soil so that the other end extends outside. A methyl bromide container is attached to this end of the tube, and the required amount of fumigant is allowed to pass through it. No pump is necessary as the methyl bromide is under gas pressure in the container if the temperature is above its boiling point. Any which comes through the tube in liquid form is caught by the container and evaporates very quickly. The cover is left in place for 24 to 48 hours.

Where the best possible control of nematodes is required or where crops are to be planted in rows less than 24 in. apart, fumigant is applied to the whole area of the field. This is called area or ''solid'' fumigation. ''Strip'' applications may be used where orchards are to be planted, the fumigant being applied to a strip of soil for each row of trees. Such a strip should be at least 6 or 8 ft. wide and can be conveniently fumigated by the use of a shank or plow applicator. ''Row'' fumigation is used where crops are to be planted in rows 24 in. or more apart, one, two, or three lines of fumigant being centered on the row. This requires some definite method of marking the locations of the rows so the seed or transplants can be placed accurately in the center of the fumigated soil. This may be easily done by forming a raised bed as the fumigant is applied, by marking the row location with a shallow furrow, or by reference to the tracks left by a tractor applicator. ''Site'' fumigation is used in orchards or where individual trees or shrubs are to be planted. A site for each tree, usually 6 to 8 ft. in diameter, is fumigated by means of a hand applicator. Where crops are to be planted in widely spaced hills, ''spot'' fumigation can be used. Locations of the hills are marked and one or several applications centered on each by use of a hand applicator. The advantage of the strip, row, site, and spot methods is the saving in the amount of fumigant required.

### 5. *Soil Factors*

The best results with soil fumigation are obtained with mineral soils of the lighter types, such as sandy loams. Fumigation of very heavy soils, particularly those of high water holding capacity, are often disappointing. Muck or peat soils can be fumigated, but require 50 to

100 per cent increases in the amount of fumigant applied per unit area for results comparable to those obtained on mineral soil.

All the soil fumigants must be applied long enough before the crop is planted to allow time for disappearance by diffusion and evaporation. This period varies with the fumigant used, the amount applied, the type of soil, and temperature and moisture conditions of the soil after fumigation. Apparently most fumigants diffuse out of the soil rather than decompose, and rate of diffusion depends on vapor pressure. Consequently ''aeration'' of cold soils is slower than ''aeration'' of warm ones. Light soils or dry soils aerate faster than heavy or wet soils, and disappearance from mineral soils is faster than disappearance from muck soils. The intervals between fumigation and planting mentioned previously are ample for fairly warm and dry weather, but must be increased in cool, wet weather. If convenient, soil can be fumigated several months before planting without conspicuous loss of efficacy. Soil is often fumigated in the fall for planting in the spring.

Preparation of the soil for fumigation involves plowing, harrowing, and leveling. There should be no large clods and plant debris should be well cut up and turned under. With some fumigants, it is also necessary that remains of infected roots should be well rotted. Large pieces of debris such as cornstalks interfere seriously with operation of shank applicators. At the time of fumigation, soil moisture should be neither very low nor very high, but about right for germinating seed.

## III. The Effects of Soil Fumigation

### 1. *Effectiveness*

At least 80 per cent and often more than 95 per cent of the nematodes in the soil will be killed by the recommended application of soil fumigant. This enables the plants to form root systems comparatively free of nematode galls or lesions. Since these abnormalities tend to shorten the roots and to reduce the number of lateral rootlets, there will be a marked increase in the length of roots and in the number of lateral rootlets. There may also be a distinct difference in color of the root system, since it will be largely free of discolored areas due to attacks of the nematodes and the secondary bacterial or fungal rots that follow their attacks. The improved root system promotes improved growth, vigor, and generally more healthy appearance of the plants as shown by increases in size and a darker green color of the leaves. There is a tendency toward more uniform growth. Provided other conditions are favorable, yield increases naturally follow, usually with improvement in quality. Yield increases of several hundred per cent are not uncommon, but average yield increases are usually around 25 to 50 per cent. With tuber or root crops, improvement in quality through the elimination of culls due to nematode damage is particularly important.

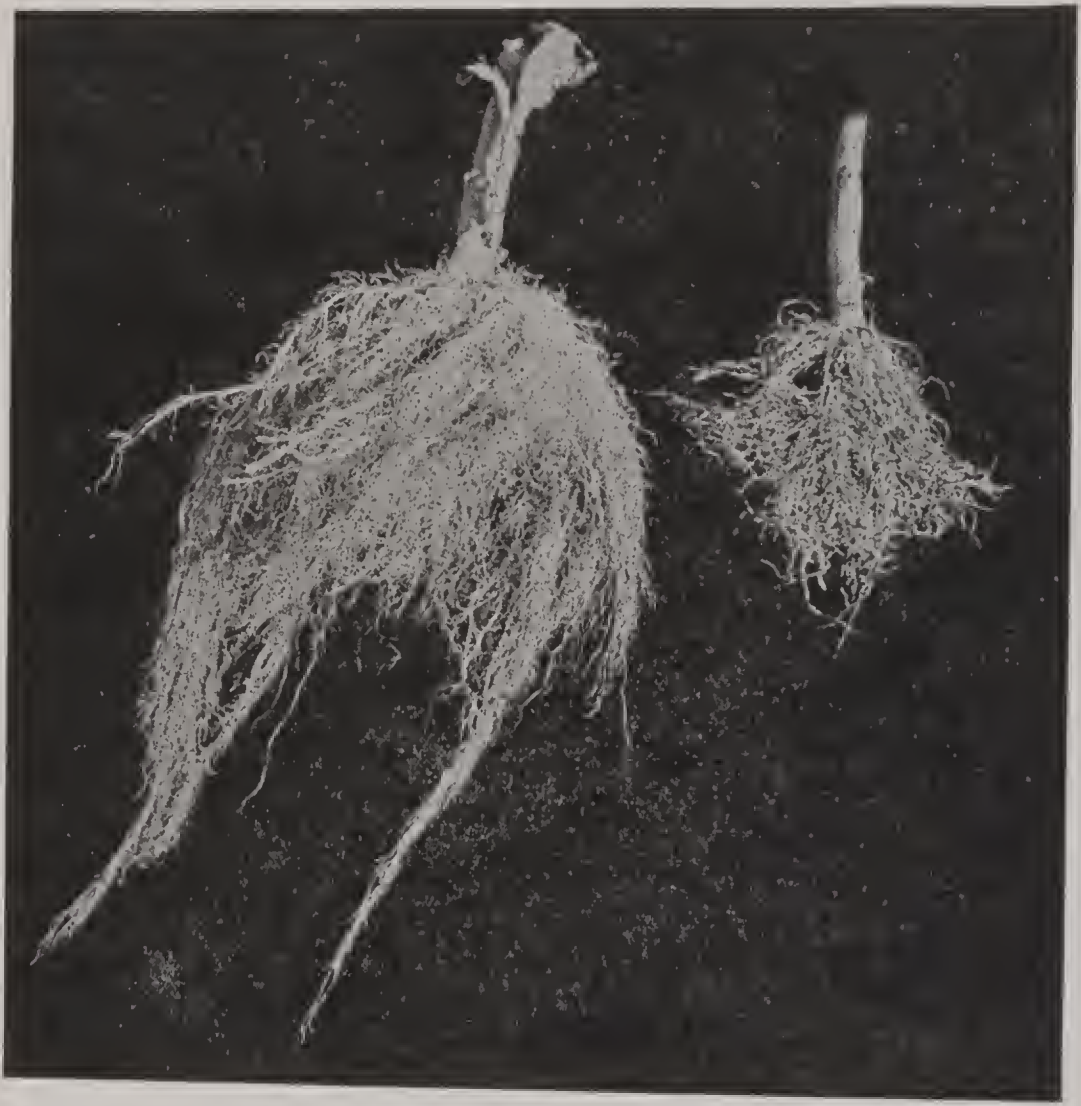

FIG. 2. Tobacco roots from a field in South Carolina. The root on the left came from soil fumigated with dichloropropene mixture and the root on the right grew in adjacent unfumigated soil. (Photograph by Shell Chemical Corporation.)

These effects will be most conspicuous in the first crop after fumigation and may or may not be appreciable in subsequent crops. Optimum applications of soil fumigants are not designed to eliminate all the nematodes but to reduce the population to the point where maximum returns are obtained in proportion to the amount of fumigant used. The remaining nematodes will attack the crop and will reproduce on it, so the population will eventually return to its former level. This will require more or less time according to the number of nematodes left alive, the crop grown, the length of the growing season, the rate of reproduction of the nematodes as conditioned by soil temperature, and other factors. These variations make it difficult to predict whether or not the effects of the fumigant will be appreciable on succeeding crops unless experience with similar conditions can be used as a guide. Row and spot treatments will certainly be effective for only one crop.

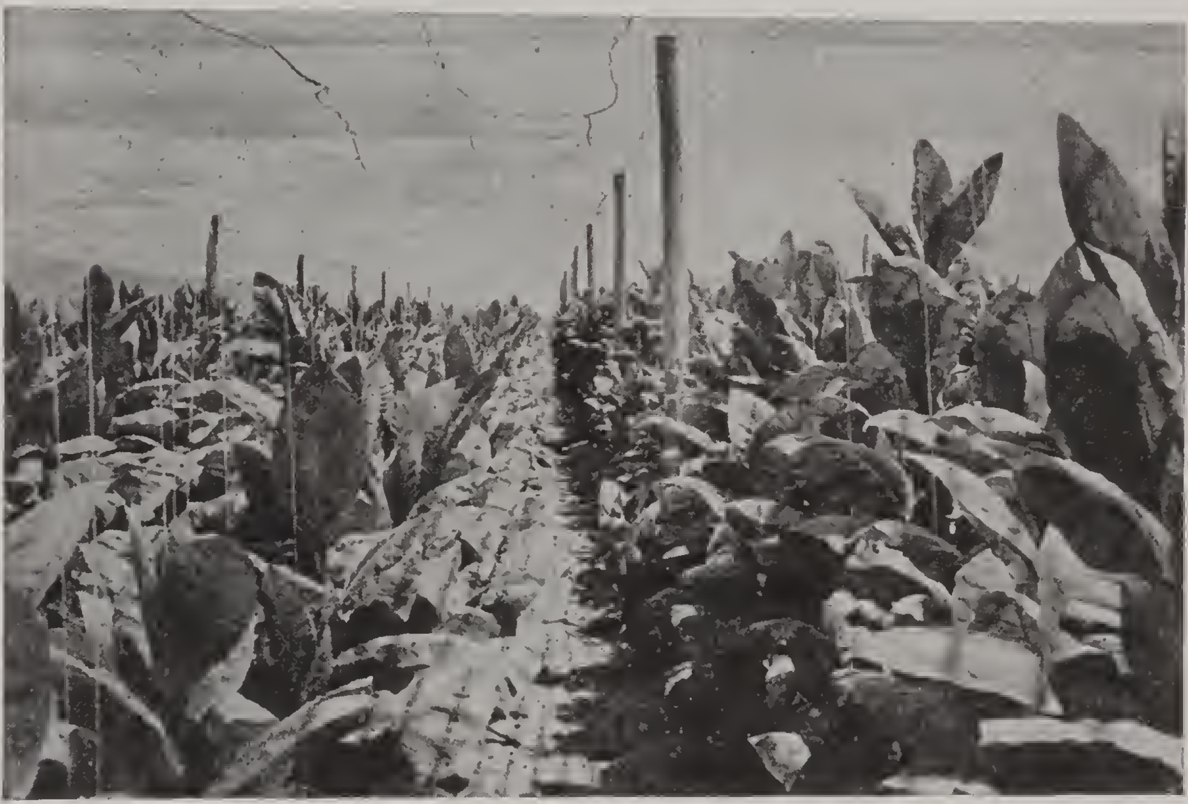

FIG. 3. Shade (cigar wrapper) tobacco growing in a field near Quincy, Florida. The soil to the right of the center was fumigated with dichloropropene mixture, and the soil to the left of center was not fumigated. (Photograph by U.S. Department of Agriculture.)

Insects which happen to be in the soil at the time the fumigant is applied will usually be killed or driven out. Some species, notably wireworms, can be controlled effectively in this way.

Sufficiently large applications of chloropicrin or methyl bromide will kill or prevent germination of many kinds of weed seeds with consequent reduction of expensive hand-weeding operations in nurseries and seed beds.

Fumigation of the soil used for seed beds increases growth and improves the root systems of transplants, besides greatly reducing the danger of contaminating the fields where they are to be planted. Next to increase of the nematodes left in the soil after fumigation, infected plants or the nematodes in soil clinging to their roots is the most important source of contamination of fumigated soil.

While soil fumigants as applied for nematode control are not efficient for the control of soil fungi and bacteria, there is evidence that they do have some effect on these components of the soil flora. Abnormal accumulations of ammonia nitrogen in fumigated soil for several weeks after the application have been reported by Tam and Clark (1943), Kincaid and Volk (1949), and Anderson (1950). This is apparently due to reduction in the numbers of nitrifying bacteria, but has not been reported as a serious matter from the practical standpoint. Considerable reductions in *Fusarium* wilt of cotton have been reported by Smith (1949), after fumigation of the soil with ethylene dibromide and with dichloropropene.

Growth of perennial plants can also be increased by fumigating the soil before planting, since the reduction of the nematode population permits establishment of a larger and better root system than would otherwise be developed. Increased growth of young peach trees in fumigated soil has been demonstrated many times.

While it is theoretically possible to kill nematodes around the roots of growing trees by applying soil fumigants, this is not advised at the present time because of the serious risk of damage to the tree.

### 2. *Economics*

The optimum application of soil fumigants containing 20 per cent of ethylene dibromide by volume, where used in ''solid'' or area application is 15 gallons per acre and the price of these fumigants is $2.25 per gallon, making the cost per acre $33.75.* For dichloropropene mixtures, the optimum application rate is 20 gallons per acre, and the price per gallon is $1.65, so cost per acre is $33.00. Chloropicrin is usually applied at the rate of about 500 lb. per acre at a cost of $400. Methyl bromide solutions used at the rate of 480 lb. per acre cost $153.60. One pound of 98 per cent methyl bromide is used for each 100 sq. ft. of soil, and the price is 75¢ per pound, so the per acre cost is $326.70. These figures do not include cost of application, which for liquid fumigants applied by tractor applicators will probably average $4 or $5 per acre.

The practical grower does not consider any expenditure on production of a crop to be justified unless there is a fair prospect that the value of the increase in yield will amount to at least twice the necessary investment. This consideration limits the use of area or solid applications of ethylene dibromide or dichloropropene fumigants to soil where the value of the crop increase will be about $75 per acre. Thus, if the expected crop increase due to fumigation is 25 per cent, the gross value of the crop should be at least $375 per acre. These fumigants are used on soil for growing tobacco, vegetables, potatoes, sugar beets, flowers, and other crops of similar value.

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* Rates of application are those found to be optimum for mineral soils and annual crops in many locations. Prices are approximate retail prices for drum lots (or other large containers) in the continental United States for 1950.

The use of chloropicrin and methyl bromide is feasible only for crops of very high value, such as greenhouse crops, seed beds, and nurseries.

Cost per acre of strip, row, site, or spot fumigation is in proportion to the fraction of each acre to which the fumigant is actually applied, the amount of fumigant per square foot being about the same as for area fumigation in most cases. Thus, row, strip, or site fumigation may cost only one-fourth to one-half, and spot treatments one-tenth as much as area fumigation or even less.

### 3. *Determination of Practicability*

If plants susceptible to nematode attack are growing in a field, determination of the approximate degree of infection by examination of the roots or other plant parts is comparatively simple and easy when the symptoms of attack are easily recognized, as with root knot for example. It is also possible to examine the soil itself for the presence of nematodes, but this is a procedure of very doubtful utility except in the case of the cyst-forming nematodes of the genus *Heterodera,* which can be estimated with a fair degree of accuracy. Adults and larvae of other forms can be isolated from the soil, but accurate estimation of the population is difficult and laborious because of the large numbers of samples required and the considerable time necessary for examination of each sample. Furthermore, populations of many species of plant parasites fluctuate widely from season to season and may be underestimated, if samples are taken when the population is not at its maximum.

Where experience with similar conditions is lacking, the best way to determine the practicability of using soil fumigants is by trial on one or several plots in the field in question. Plots may be arranged to compare yields on fumigated and unfumigated soil, to compare different fumigants, rates or methods of application, and so to provide data on which to make the decision as to the advisability of fumigating the whole field for subsequent crops. Results of fumigation tests under similar conditions in near-by fields are also a valuable guide.

Where nematodes are known to be present in significant numbers, the desirability of trial applications of soil fumigant is evident. Considerable experience with soil fumigation indicates that trials should also be conducted where the degree of nematode or other soil pest infestation is not known, but where yields have declined over a period of years, growth of crops is not uniform, or root systems are poor. Such tests have often revealed the occurrence of nematode damage where it has been unsuspected or attributed to other causes.

### 4. *Future Prospects*

Exact information is not available, but it is estimated that soil fumigants of various types for fumigating more than 100,000 acres were produced in 1950, the largest part of these being ethylene dibromide and dichloropropene. Their value was in excess of $4,000,000, and the value of increased production due to their use was several times this amount.

Further development depends to a large extent on increased realization by growers of the possibilities and advantages of soil treatments. Even so, use is limited by the cost of the present materials. Less expensive soil treatments would open up tremendous new markets and increase the volume of business in those now existing. The possibility of controlling soil insects, nematodes, bacteria, fungi, and weeds, and the feasibility of doing so on crops of fairly high value has been demonstrated. Further improvements in materials and methods will open the way to eventual elimination of one of the principal limiting factors in crop production.

## IV. SUMMARY

Although the idea of killing nematodes in the soil by fumigation is about 75 years old, a practical method of doing so was not developed until after 1930, when chloropicrin was first used on a large scale for this purpose. Further progress came with the recognition of the nematocidal value of methyl bromide in 1940, dichloropropene mixtures in 1943, and ethylene dibromide solutions shortly thereafter. Other soil fumigants are in the early stages of development.

Practicability of soil fumigation depends on the ability of vapors to permeate the upper layers of the soil and to kill a large proportion of the plant parasitic nematodes and other soil pests there. Because of convenience of application and favorable properties of the fumes, most soil fumigants are volatile liquids, but methyl bromide is also applied as a gas. Liquid soil fumigants are applied by placing them under the soil surface, usually at a depth of 6 or 7 in., and at intervals of 10 to 12 in. Machines for this purpose are readily available. Methyl bromide is applied as a gas under an impermeable cover placed over the soil. Good results are obtained by application of fumigants to the whole area of the field, or to only those portions which will be occupied by the roots of young plants. Application is made to soil prepared as for planting, but several days or weeks before the crop is planted to permit diffusion of the fumes from the soil. This is necessary because soil fumigants are also somewhat toxic to plants. Mineral soils of the lighter types are most favorable for fumigation, but peat soils can also be fumigated satisfactorily if the application rate is increased.

The usual effect of fumigating the soil is the killing of a large proportion of the nematodes, but complete extermination is seldom obtained. With optimum applications, enough nematodes are killed to protect the plants from damage in the early stages of growth when they are most vulnerable. The limited mobility of nematodes prevents rapid reinfestation of fumigated soil by migration from adjacent unfumigated areas, and the comparatively slow reproduction of plant parasitic nematodes prevents rapid increase of the small proportion of the population left alive. However, with these and other sources of reinfestation, notably infected transplants, the nematode population will eventually return to its former level. The intervals necessary for this increase depend on the interrelationships of several factors, and in any given case, it is difficult to predict whether or not crops succeeding the first one after fumigation will be benefited.

The elimination or considerable reduction of nematode attack permits the plant to form a normal root system, with consequent improvement in growth, yield, and quality. Yield and crop value increases of several hundred per cent are not uncommon after fumigation of heavily infested soil, but averages are in the range of 25 to 50 per cent.

Cost of the usually recommended applications of dichloropropene or ethylene dibromide fumigants is about $37, and these are profitable for use on crops having a gross value of $375 per acre, if increases of 25 per cent in the value of the crop can be obtained. Methyl bromide and chloropicrin are much more expensive and are used where crops of very high value are grown in greenhouses, seed beds, and nurseries. Strip, row, site, and spot fumigation are less expensive in proportion to the fraction of the area of the field fumigated and are profitably used on crops of lower value.

The practicability of fumigating a certain field can be determined by examination of nematode susceptible crops growing on the field, if the symptoms of attack can be easily recognized, but the best method is the use of trial plots, since these have the advantage of demonstrating the effect of fumigation by yield increases. Examination of the soil for nematodes is impractical with many species because of the time required for adequate sampling and the possibility of underestimating the infestation if samples are not taken when the population is at its maximum.

It is estimated that the production of fumigants in 1950 was sufficient for treating more than 100,000 acres, and that the retail value of the fumigants was in excess of $4,000,000.

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# Problems and Progress of Soil Conservation*

HORACE J. HARPER
*Oklahoma Agricultural and Mechanical College, Stillwater, Oklahoma*

## CONTENTS

*Page*
I. Introduction . . . . . . . . . . 265
II. Education and Financial Incentive Increase Conservation . . . . . . 267
III. Research for Soil and Water Conservation . . . . . . . . . . . . 273
  1. Land Classification Problems . . . . . . . . . . 275
  2. Cropping Systems . . . . . . . . . . 277
  3. Terracing and Contour Farming . . . . . . . . . . 281
  4. Grassed Waterways . . . . . . . . . . 285
  5. Infiltration and Run-off . . . . . . . . . . 286
  6. Crop Residue Management . . . . . . . . . . 290
  7. Soil Loss and Land Use . . . . . . . . . . 294
  8. Pastures . . . . . . . . . . 297
  9. Strip Cropping . . . . . . . . . . 300
  10. Shelter Belts . . . . . . . . . . 302
  11. Economic Problems . . . . . . . . . . 304
  12. Social Problems . . . . . . . . . . 309
IV. Summary . . . . . . . . . . 311
References . . . . . . . . . . 319

## I. INTRODUCTION

During the past fifty years general interest in the conservation of natural resources has developed rapidly in the United States due to the leadership of a few people. So far as soil and water conservation are concerned, only a beginning has been made in the herculean task of protecting the land from erosion and increasing the effective use of rainfall. The art of erosion control has been practiced for centuries on cultivated land. It involves the use of vegetative and mechanical procedures to slow down the movement of run-off water, and in some areas the use of simple practices to reduce the hazards of wind erosion. Within recent years the popular name of soil conservation has been applied to the beneficial effect obtained from the use of one or more methods to control soil erosion. The principal objective of soil conservation is to manage the land so that the physical value of the soil will be preserved for future use. It is a profitable procedure in so far as it permits the farmer to utilize added or natural fertility which would otherwise be carried away by water or wind.

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* The term conservation was deliberately adopted in 1907 as a name for a movement in the United States to capture the imagination of the nation which was to be awakened to the problems of its resources. The term conservation was and is used not only for nonexpendable resources which were to be kept under present level productivity, but also for expendable resources which are necessarily depleted through use. (*Journal of Farm Economics* 1942. 24, 75-96.)

Taylor (1950) refers to "Soil conservation as a movement," Sears (1950) says, "It is an attitude." In reality soil conservation is an achievement principally on sloping areas of cultivated land. The problems of soil conservation in the United States have been described by Bennett and others (1947). It is quite evident from these reports that misuse of land can occur under many different conditions. Soil conservation in some areas is the big problem. Many soils in semi-arid and arid regions contain a sufficient quantity of available plant nutrients to produce maximum crop yields under the climatic conditions which prevail. On these areas good management of the land consists primarily in the adoption of methods which conserve the soil and increase the efficiency of rainfall. In 1946 the Secretary of the United States Department of Agriculture reported that soil-conserving practices are not required on 75,000,000 acres of land in this country. On this land soil-improving practices, which include the use of lime, fertilizer, and soil building legumes in the cropping system, are the important treatments needed to maintain crop production. In other areas maintaining soil fertility is not enough on sloping land. The physical value of the soil also must be preserved. Under such conditions both soil-conserving and soil-improving practices must be used to maintain a prosperous and productive agriculture. The continued production of row crops on sloping land has been responsible for most of the damage caused by soil erosion. How to reduce the acreage of row crops is the big problem.

The principal objectives of erosion control are very simple. They are accomplished by using vegetation and mechanical procedures to protect land from excessive erosion by retarding the flow of run-off water and preventing soil movement by the wind. If farmers in the northeastern states who normally use sod crops and small grain in their cropping systems would change to contour strip farming, the biggest erosion problem in that area would be solved. In the grassland area of the midwest and western states the principal cause of soil erosion has been an increase in run-off from over-grazing on the steeper slopes. Regulated grazing is the only economical procedure that can be used to solve the erosion problem on much of this land. In some areas reducing the acreage of row crops on moderate and steep slopes must occur to slow down soil erosion sufficiently so that farmers can continue to cultivate the land. When farmers are not producing livestock, but must plant some of their land to pasture or a feed crop to preserve the soil, a shift in farming system will be required. In some instances cultivated land should be planted to forest to conserve the soil. Such changes will not be made in many instances except under the influence of economic pressure.

Much technical information has been supplied by the soil physicist, the soil biologist, the crop specialist, the soil surveyor, the agricultural economist, and the agricultural engineer concerning the need for and value of various mechanical and vegetative procedures for erosion control on different types of land. However, the biggest problem in soil conservation at the present time is a human problem. Progress will be made as farmer interest increases, or as necessity demands it.

## II. Education and Financial Incentive Increase Conservation

A lack of soils education has been one of the important factors which has retarded the progress of soil conservation in many areas. People must understand why a particular job must be done and how to do it before much participation will be obtained. Bennett (1921) wrote a book on the soils of the southern states and emphasized that erosion was a problem of some importance. Suggestions for controlling erosion were as follows: (1) steep slopes should be planted to soil-binding crops for forage production, and (2) terraces and contour tillage should be used on erodible areas where such procedures have not been established. Deeper plowing, liming, fertilization, and the use of legume rotations were recommended to increase soil productivity. He concluded that conservation of soil itself was a larger problem than the conservation of soil fertility in the southern Piedmont area.

County agents and others who helped to establish terracing and contour farming on several million acres of land prior to 1933 did an excellent job. It was difficult to convince even many progressive farmers during the initial stages of a soil erosion control program that they should establish soil-conserving practices on their land. Regardless of the efforts of these pioneers to control erosion, soil conservation did not keep pace with soil deterioration. Unfortunately the harmful effect of soil erosion in its initial stages was not recognized on many soils, because no great reduction in soil productivity occurred during any one year. Where nothing is done to control sheet and gully erosion, or to increase soil fertility, the productivity of some cultivated land will gradually decline, principally because of a reduction in the physical value of the soil. Under many conditions the income from the land may be so low before the farmer realizes that something should be done to control erosion, that he is unable to change his farming procedure to cope with the problem. Education alone is of little help to such individuals.

For the past thirty years, the federal government in the interest of future security has been concerned with agricultural policy as it related to better land use. In 1933, the federal government, faced with a serious problem of unemployment, overproduction, and low prices for agricultural products, and severe drought in some areas, initiated a series of action programs of which the Civilian Conservation Corps, the Works Progress Administration, the Agricultural Adjustment Administration, the Soil Erosion Service, and the Tennessee Valley Authority became involved in a conservation movement.

The Soil Erosion Service was set up in the Department of the Interior in September, 1933, with a budget of $5,000,000 from the Public Works Administration for the twofold purpose of controlling erosion and supplying jobs for unemployed people. Additional appropriations from relief funds helped to expand field operations. On May 11, 1934, when the Congressional Committee hearings were being held to consider the value of soil conservation work and to argue whether the program should be continued, dust swept up from unprotected fields in the Great Plains area and filtered through the open doors and windows of the Capitol in Washington, D. C.* This phenomenon made both rural and city people conscious of the fact that something was wrong with the land. In 1934 the Soil Erosion Service was transferred from the Department of Interior to the Department of Agriculture and renamed the Soil Conservation Service. This organization with a well-financed section on information, has published millions of pamphlets, and its representatives have made many personal contacts with teachers, preachers, politicians, social clubs, and chambers of commerce, and has been instrumental in holding meetings with businessmen and farmers to warn them of the serious impact which uncontrolled soil erosion would eventually produce on both rural and urban areas.

The field demonstration program of the Soil Conservation Service was started on several watersheds in different parts of the country in 1934. Cooperating farmers furnished the land and some labor. The Soil Conservation Service, fortified with help from the Civilian Conservation Corps and the Works Progress Administration, supplied machines, materials, and technical assistance to establish a soil conservation program on the land. In some watersheds the cost of the program was about equal to the value of the land treated. Many of the soil-conserving practices established on some of these farms were abandoned after the five-year contract with the Soil Conservation Service expired, because the farmer had not been educated sufficiently to understand that the control of soil erosion will require the use of less convenient procedures, such as more labor to plow the fields and to plant, cultivate, and harvest the crops. These demonstrations had different effects on different individuals. Although many farmers who visited them recognized the merit of various soil-conserving procedures, a comment frequently heard when one neighbor would be talking to another was, ''Don't get in a hurry; the government will do it for you.'' However, the effect of the watershed demonstrations combined with the educational influence previously exerted by the Agricultural Extension Service in many states convinced many farmers outside of the watershed areas of the need for erosion control. A higher percentage of the farmers in some project areas established soil-conserving practices on their land where only technical assistance was supplied than was obtained when the soil conservation program was first started on watershed areas where a major portion of the cost of erosion control practices was paid by the federal government.

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* Since that period the pendulum has swung in the opposite direction. More favorable rainfall has brought prosperity to the Great Plains area. Soils that appeared to be badly damaged because of wind erosion began producing 25 to 35 bushels of wheat per acre. Pastures which were parched and dry revived quickly and excellent pasture has reappeared on most of the land.

In 1937 a model Soil Conservation District Law was worked out by the land policy committee of the Soil Conservation Service assisted by political scientists, economists, agricultural specialists, and lawyers. The objective of this law was to encourage local interest and responsibility in the development of a soil-conserving program. It had both an educational and a political value. On June 30, 1949, there were 2,139 soil conservation districts in the United States containing over 4.5 million farms and ranches with active conservation plans on 665,000 farms. Several thousand soil conservation district supervisors have the responsibility of stimulating local interest in conservation planning. The Soil Conservation Service will continue to supply technical information for erosion control to these districts as long as federal funds are appropriated for this purpose.

More recently the educational phase of the soil conservation program in soil conservation districts has been based on group activity. Group planning helps each farmer to solve his own problems by discussing them with his neighbors. When one farmer tells another how he accomplished a particular soil-conserving job, the beneficial effect of such information is likely to spread to adjacent land much more rapidly than if the only source of information was the local representatives of the Soil Conservation Service working in the area.

In 1938 a reorganization in the U.S. Department of Agriculture transferred all action phases of the physical land use adjustment programs including such items as erosion control, water facilities, submarginal land purchase, farm forestry, irrigation, and drainage to the Soil Conservation Service. Consequently, some of the activities of this organization, such as land drainage, which is a soil-exploiting procedure, are not directly associated with soil conservation. "Land Management Service" would be a more appropriate name for the Soil Conservation Service because it would be more applicable to the many land use programs and projects supervised by this agency. The success of a soil conservation program in many areas often depends upon the use of other good farm management practices along with methods for erosion control and water conservation. Consequently, some soil conservationists realizing the limitations of their program have pleaded for a broader viewpoint of soil conservation which would give them authority to do anything that needed to be done on the land. What they actually desire is the official approval for greater freedom of action. Since a successful farm management program must include much more than soil conservation there has been a tendency for the soil conservationist to help with all phases of pasture and range improvement, cropland, orchard land, and woodland problems, soil fertility improvement, fish pond and wild life projects, drainage and irrigation problems, etc. The expansion of a soil conservation program to include many nonrelated activities has caused some confusion among both technical and nontechnical people engaged in other agricultural production and research programs.

In 1933 the Tennessee Valley Authority was created to carry on a broad program of coordinated land use in a specific area. The program was a combination of education and financial incentive. The farm demonstration phase of this program was confined principally to crop adjustment and an increase in the use of soil-improving and soil-conserving practices. Before the Tennessee Valley project was started, many of the soils in that region were nonproductive, and the people on the poorer soils were among the most poverty stricken and backward of any area in the United States. Through necessity they were in the front rank of the eroders and devastators. The introduction of contour plowing, terracing, improvement of farm woodlands, along with the use of lime and phosphate to increase the yields of legumes grown in the cropping system, and a livestock improvement program on 20,000 demonstration farms scattered among 225,000 other farms in this region, has had an important influence on farm income. The accomplishments on these demonstration farms have been of great educational value to the communities in which they are located. Standards of living have improved and 1,350,000 farm people have not only become more prosperous and competent, but also are better fed and better clothed. Better roads, better schools, and better churches have been made possible because of better economic conditions brought about by a better combination of soil-improving and soil-conserving practices combined with better livestock and cash crop enterprises (Lilienthal, 1944).

The Taylor Grazing Act passed by Congress in 1934 was the first step toward the protection of over 100,000,000 acres of western range land owned by the federal government. Over-grazing of this land during periods of drought had greatly reduced the carrying capacity in many areas. The development of state grazing commissions in Montana and in the Dakotas made it possible for farmers, who knew the problems associated with range land conservation, to form local grazing associations which permit the members to raise cattle under controlled conditions in common pastures. The greatest conservation benefit from controlled grazing is obtained from an increase in vegetative cover which indirectly protects the soil by decreasing run-off.

Another federal agency, the Agricultural Adjustment Administration, was set up in 1933 after a period of overproduction and low prices, for the purpose of crop acreage control and to stimulate the use of practices which would improve and conserve the soil. The crop reduction phase of this program made a majority of the farmers conscious of an agricultural problem. Since 1936 this agency has been providing financial aid to farmers who have applied for help to establish soil-improving and soil-conserving practices on their land. This program has an educational value in areas where good land management practices are needed to improve or conserve the soil. In older agricultural areas where soil-improving practices have become a part of good land management, financial aid for soil improvement is a subsidy which may be justified because of a public interest in maintaining soil productivity for future security.

Since the close of World War II, farmer interest in erosion control and reclamation of eroded land has been increasing. Favorable prices for livestock have stimulated an interest in pasture improvement on many acres of formerly cultivated land. Planting legumes for soil improvement, terracing, contour farming, and mulch tillage to control erosion or increase infiltration of rainfall have increased. To what extent educational activity or incentive payments have been responsible for an increase in soil-conserving and soil-improving procedures might be rather difficult to determine. A study of soil conserving accomplishments of the Production and Marketing Administration and the Soil Conservation Service from 1946 to 1948 inclusive, is given in Table I. The practices reported by the SCS are newly applied, whereas some duplication of

TABLE I

Conservation Practices Reported by the Soil Conservation Service and the Production and Marketing Administration of the U.S. Department of Agriculture (1946 to 1948, inclusive)

| Practice | Soil Conservation Service [a] | Production and Marketing Administration [b] |
|---|---|---|
| Contour farming | 9,527,055 acres | 23,631,979 acres |
| Cover cropping | 6,263,686 acres | 51,123,535 acres |
| Stubble mulching | 15,593,314 acres | 16,835,344 acres |
| Strip cropping | 2,008,049 acres | 1,564,961 acres |
| Seeding range and pasture | 4,983,514 acres | 13,176,541 acres |
| Farm and ranch ponds (number) | 81,642 | 311,125 |
| Tree planting | 170,349 acres | 150,045 acres |
| Terraces | 283,492 miles | 223,614 miles |
| Sod waterways | .............. | 103,223 acres |

[a] Report of the chief of the Soil Conservation Service, 1949, p. 14.

[b] Conservation Practice Summary, 1936 to 1948, PMA, U.S. Department of Agriculture, January, 1950.

acreage may occur in the PMA data. It is quite probable that many of the completed practices on farms where a soil conservation plan has been prepared by SCS personnel would not have been accomplished if the farmer had not been provided with financial aid. The extent of soil conservation and improvement on many farms is determined by the amount of assistance obtained from PMA. From 1936 to 1946, 672,000 miles of terraces were built by farmers cooperating with the PMA agricultural conservation program.

Less than 19 per cent of the land in the United States has been treated under a farm or ranch conservation plan prepared by the SCS, and much of this area is pasture land where controlled grazing is the most important practice required to protect the soil from erosion (Bennett, 1950). Also less than half of the farmers in the nation's 3,000 counties have received financial assistance through the agricultural conservation program of the PMA. It is quite evident that the job of controlling soil erosion on sloping areas of cultivated land has just begun, and stupendous losses in potential productivity of cultivated land on moderate and steep slopes will occur unless the present rate of progress can be greatly accelerated.

So long as federal and state laws provide individual freedom in the use of land, there will be many farmers who will turn a deaf ear to any educational appeal or financial incentive which may be made to aid them in conserving or improving their soil when such a program runs counter to their immediate economic interests. Benedict (1937) is of the opinion that a more adequate coordination of the activities in several federal departments dealing with agricultural conservation, both in the matter of objectives and of functions, is a vital necessity. Some progress has been made, but the situation still remains one of the major inefficiencies of the federal government.

One of the educational problems of soil conservation occurs in secondary schools. Information on soil conservation should be more carefully integrated into many soils courses because erosion control is one of the essentials of good soils management on cultivated land. This relationship is shown in Fig. 1. Soil improvement is an important problem on all humid soils, whereas, both soil improvement and soil conservation are problems on sloping areas of cultivated land, the importance of the soil-conserving practices increasing with degree of slope. Bennett (1939) has written a textbook which can be used as a source of reference material for a soil conservation course. Classification of land according to susceptibility to erosion would be taught normally as a part of a course in soil morphology. Usually the engineering aspects of erosion control are taught in the department of agricultural engineering.

Several state departments of education have published material on conservation for use in primary schools. The tendency has been to integrate such information into several courses rather than to present it as a single subject.

The importance of soils education and research is often overlooked, or its value is underestimated by many people who are in a position to do something about it, such as administrators in agricultural colleges because their primary interest or training has been in some phase of crop or livestock production or in a nonagricultural field. Judging contests and shows in crops, poultry, livestock, and livestock products have attracted public interest because of the glamour associated with them. Recently, Roberts (1950) of Oklahoma developed a plan for a land judging contest and has held many of these contests for students in the Veterans Agricultural Training Program, in vocational agriculture, and in 4-H clubs.

## III. Research for Soil and Water Conservation

Research for soil and water conservation has two principal objectives. One objective has been to obtain quantitative data on the losses of soil and water under systems of poor land management to emphasize the need for erosion control and water conservation. The other objective has been to examine and evaluate various mechanical and vegetative procedures which may be used to protect the land from the destructive effect of run-off water or wind under varying soil and climatic conditions. Some of the problems which a large research staff has been studying under different soil and climatic conditions in many states are terracing, contour farming, strip cropping, crop rotations, cover crops and tillage methods for soil conservation, the effect of soil texture, structure, vegetative cover, land slope and rainfall intensity on the absorption of rainfall, the disintegration of soil structure on bare land by the force of raindrops and the sorting effect of splash erosion, the establishment of grassed waterways and water disposal systems for terrace outlets, the effect of over-grazing of range lands and the burning of forests on soil and water losses, the effect of social and economic forces which may accelerate or retard the expansion of soil conservation practices, the search for better types of grasses and legumes to control soil erosion under varying conditions, the effect of soil erosion on the sedimentation of reservoirs and the influence of soil-conserving practices on flood control. In addition, many problems relating to land drainage and irrigation are being investigated.

Most of the procedures for the control of both wind and water erosion were well understood by scientific people and were being practiced to a limited extent on many farms before the first of ten Federal Erosion Stations was established in 1929 (McGee, 1911). During the past twenty years volumes of literature * have been published on various phases of the erosion and water conservation problem. A discussion of soil and water conservation problems in different parts of the United States and a description of some procedures which have been used to correct them have been presented by Bennett *et al.* (1947).

Although a large number of procedures may be required to control water and wind erosion under various soil and cropping conditions in different parts of the United States, anyone familiar with this problem knows that most of these problems can be solved by the application of a few simple practices which normally should be classified with the art rather than with the science of agriculture. A brief discussion of land classification, crop rotations, terracing and contour farming, grassed waterways, infiltration and run-off, crop residue management, soil loss and land use, pasture problems, strip cropping, shelter belts, economic and social problems as they relate to erosion control and water conservation will be presented in the following paragraphs.

* Research summaries and abstracts of recent published material on soil and water conservation have been prepared since 1945 by J. H. Stallings, Soil Conservation Service, Washington, D. C.

### 1. *Land Classification Problems*

Classification of land according to erosion susceptibility is the basis of a soil conservation program. Soils have been classified and maps have been published by the Division of Soils of the U.S. Department of Agriculture, on a scale of 1 in. per mile for the past fifty years. These maps show the general soil characteristics of an area, but the scale is too small to show some physical features that are helpful in the preparation of a farm plan to conserve the soil. In 1933 Glen L. Fuller, of the Soil Conservation Service, developed a mapping procedure to show, in addition to the soil types, the shape of the fields, vegetative cover, extent of sheet and gully erosion, and the slope of the land (Hartman and Wooten, 1935). In some areas a scale of 8 in. per mile was used in making these maps. Aerial photographs with a scale of 4 in. per mile have been used extensively as a physical base for soil mapping since 1938.

Since the personnel of the Soil Conservation Service was assembled rapidly, many individuals with little or no previous experience in soil classification were assigned to the job of mapping soils. The problem of recognizing transitional soils and a system of mapping which provided for many slope separations and different degrees of sheet and gully erosion resulted in an enormous number of soil-slope-erosion combinations which often increased in complexity on poor land. The confusion arising from inaccurate soil classification in some instances, plus excessive detail with reference to slope and kinds of erosion, made it difficult for other quickly trained personnel who were assigned to the job of applying soil conserving procedures on the land to evaluate the soil maps in terms of cropping systems and the various mechanical and vegetative treatments required to protect different fields from the harmful effect of run-off water or wind erosion. It is quite probable that a soil conservation slogan, "Each acre to its proper use," originated during this period.

The complexity of the earlier soil conservation maps greatly reduced their usefulness on some farms where common sense indicated that all the land should be treated in a similar manner to conserve the soil. In one area an attempt was made to use a reconnaissance soil survey which shows only major soil variations. This type of map was also of little value to farm planners who knew very little about soil classification. However, Norton (1939) brought order out of chaos by developing a system of land use classification based on erosion susceptibility and proper land use. Land suitable for cultivation was divided into five classes. Land which should be used for pasture was divided into two classes, and one class was reserved for nonagricultural land. Different soil types, depending principally upon their physical properties, were placed in different land classes by the soil surveyors. Cropping systems and mechanical treatments needed to protect the land from the destructive effect of soil erosion were worked out in cooperation with agronomists and engineers. Consequently an accurate soil map, correlated in terms of proper land use, made it possible for individuals knowing very little about soil origin or development to prepare a farm plan indicating any required changes in land use or cropping systems, and the need and extent of soil-conserving practices to reduce erosion loss to a point where it would more nearly approach the rate of soil formation.

Over 300,000,000 acres of land have been mapped by Soil Conservation Service surveyors for the purpose of farm planning (Bennett, 1949). The problem of mapping the degree of soil permeability accurately is probably the most difficult task of the soil surveyor. O'Neal (1949) reported that no single physical property of a soil could be used in classifying soil according to degree of permeability. All the land in some soil conservation districts has been mapped, and a few of these maps have been published. In some districts complete information concerning the physical character of the land and susceptibility to erosion may be obtained from field sheets in the local soil conservation district office. In other areas only a portion of the land in the district has been surveyed.

At the present time land use capability maps are made only of farms where individuals have filed a request with the supervisors of the local soil conservation district for technical aid. However, there is no reason why many soil-conserving practices could not be established on the average farm without the use of a soil map. According to an estimate made by the Soil Conservation Service in 1946, 125,000,000 acres of crop land needed simple contour cultivation, and another 100,000,000 acres should be strip-cropped. Where the soil conservation problem can be solved merely by changing row direction, erosion could be greatly reduced on a large area of land by simple mechanical practices. The problem, however, is not quite so simple as it may appear. Although approximately 80 per cent of the cultivated land according to the Soil Conservation Service should continue to be used for cultivated crops, the remaining 20 per cent of the cultivated land which should be changed to permanent grass land or forest before land abandonment must occur because of erosion, is probably distributed among 50 per cent of the nation's farms. Consequently, land use classification maps would be needed on at least half of the land to obtain information concerning the proper use of some areas for erosion control. Such maps also would be helpful on other less erodible areas to determine the best methods to use to conserve the soil.

Although abandoned land may be found on many farms, the limiting factor in crop production on most of this land is soil fertility. Increasing pasture production on this type of land is a problem of soil improvement. The necessary soil treatment for the crop to be planted should be determined by a careful study of the physical and chemical properties of the soil. A soil survey will show areas that are suitable for cultivation, areas that could be improved and used for pasture, and those lands which should be planted to forest. Since loss of surface soil by erosion will gradually change a moderately deep soil to a shallow soil, a knowledge of soil conditions on different farms as they may be changed by mismanagement is an important factor in the formation of a soil conservation and soil improvement program to aid in the development of a more permanent and productive agriculture on both good and poor land.

A uniform method of soil mapping has not been used in making soil conservation surveys in different parts of the United States. Recently a new system of physical soil classification has been devised so that the mapping nomenclature from different regions can be combined into a master legend to show the physical value of all land in the United States for which information is available in terms of soil depth, surface texture, permeability of soil profile, slope of land, degree of erosion, and other characteristics which may affect land use, such as drainage, stoniness, or harmful concentrations of soluble salts.

### 2. *Cropping Systems*

Row crops on moderate to steep slopes in areas of torrential rainfall are the principal cause of soil erosion. Copley *et al.* (1944b) measured the loss of soil in North Carolina from a four-year rotation and found that 90 per cent of the soil was removed from the land when it was in cotton and corn. Similar results have been obtained by other investigators. Therefore, the principal job of soil conservation is to reduce the acreage of row crops on moderate to steep slopes and to utilize other soil conserving practices to keep soil losses below a permissible maximum. The importance of this task may be more fully appreciated as a result of a report made by the Agricultural Adjustment Administration of the U.S. Department of Agriculture (1944, p. 7), which showed that the acreage of corn and soybeans increased from 50,355,000 to 67,153,000 acres in ten northern states from 1940 to 1944.

Many experiments have shown that row crops planted parallel with moderate slopes provide little protection to the land from run-off water, and that 7 in. of topsoil weighing approximately 1,000 tons per acre would be washed from cultivated land so cropped in twenty to forty years. The solution of the erosion problem on moderate to steep slopes is a complete vegetative cover during periods when heavy rains occur. Small grain, legumes, or a grass-legume combination will keep soil losses at a relatively low value under average conditions. Consequently, the problem of erosion control is much easier to solve on farms that produce small grain, hay and/or pasture than on sloping land where row crops are planted.

As soil fertility declines, good farmers normally plant soil-building legume crops which are usually seeded with or following a small grain crop. In a four-year rotation of corn, corn, oats, and clover, a row crop would occupy the land 50 per cent of the time. This type of cropping system combined with contour farming and terracing or strip cropping would solve the soil erosion problem on most of the highly productive soils in the humid portion of the United States.

An early Illinois experiment started in 1906 and reported by Mosier and Gustafson (1918) demonstrated the beneficial effect of liming, crop rotation, terracing, and contour farming on eroded land to increase crop production. In a more recent study, Duley and Miller (1923) obtained quantitative data on soil loss from row crops, small grain and hay land in Missouri, which showed very clearly the advantages of close-planted crops as compared with row crops in reducing the rate of soil loss by erosion.

Any type of cropping system can be used in a soil-building rotation on a gentle slope, since the principal problem of maintaining or improving crop production is to maintain or increase soil fertility and organic matter. However, as the slope of cultivated land increases, cropping systems for soil conservation become exceedingly important in regions where climatic conditions are favorable for the production of row crops. On moderate to steep slopes a row crop must not occupy the land more often than once in three to five years to conserve the soil (Hays and Clark, 1941).

Uhland (1949) presented data on soil loss in relation to crop production which show the need for soil conservation on cropland areas. A rotation of corn, oats, wheat, and hay on terraced and contour farmed land at Bethany, Missouri, was calculated to lose soil at the rate of 7 in. in 2,333 years, in contrast to a rate of 7 in. in 18.8 years on similar land cropped continuously to corn.

Pope *et al.* (1946) studied the effect of cropping systems on reducing soil losses on sandy timber land in east Texas and believe that a combination of improved rotations, winter cover crops, and terraces will reduce soil losses to 5 or 6 tons per acre per year on slopes of 6 to 8 per cent.

Hendrickson (1947) found that a southern Piedmont soil in South Carolina planted continuously to cotton lost an average of 28.13 tons of soil per acre each year, whereas cotton in a rotation with oats and lespedeza lost 7.08 tons per acre. The average annual loss of soil from the three crops in the rotation was 3.38 tons per acre. This reduction was partly due to the greater absorption of rain, the average loss of water being 5.18 per cent from the rotation plots as compared with 11.62 per cent on land in continuous cotton. The yield of seed cotton in the rotation was 1070 lb. per acre as compared with 785 lb. for continuous cotton. Two years of close-planted crops followed by a row crop on moderately sloping land will provide sufficient protection so that cultivated crops can continue to be grown for a long period of time. A slight increase in soil organic matter was obtained in this experiment.

Horner, McCall, and Bell (1944) reported that land in the Palouse area of Washington protected by small grain stubble or by an alfalfa-grass mixture lost no soil. A sweet clover rotation with wheat decreased soil loss from 3.05 to 0.26 tons per acre. Browning (1948) reported that changing a rotation in Iowa from corn, corn, oats, and meadow, to corn, oats, and two years of meadow reduced the average soil loss from 14 to 6 tons per year.

Page and Willard (1946) observed that a clay soil in Ohio on which corn and oats with sweet clover had been planted was nearly dry enough to plow when water was standing on similar land planted in corn every year. The productive capacity of this land decreased rapidly when a sufficient quantity of organic matter was not returned to maintain a favorable physical structure for aeration and moisture movement.

Pierre and Browning (1945) have stressed the importance of maintaining soil organic matter by means of a legume rotation to conserve the soil. Land planted continuously to corn in Iowa lost 15.6 per cent of the organic matter in nine years and an average of 38.3 tons of soil per acre annually. A three-year rotation of corn, oats, and sweet clover lost only 0.9 per cent of the organic matter and reduced annual soil losses to an average of 9.2 tons per acre during the same period. This loss occurred when corn, oats, and clover were planted parallel with a 9 per cent slope. These authors have recommended (1) a rotation of corn, corn, oats, and clover on nearly level soils, (2) a rotation of corn, oats, and clover, or corn, corn, oats, and two years of alfalfa on gently rolling land, and (3) corn, oats, and two years of an alfalfa-bromegrass mixture with mechanical treatment of contouring, strip cropping, or terracing on rolling to hilly land. Bartholomew and Carter (1939) reported that the average soil loss from a three-year rotation of corn, oats, and red clover on a Clarksville silt loam in Arkansas was 2.3 tons per acre. The land slope was 6 per cent. Loss of soil from the clover and small grain was 1.1 and 1.6 tons per acre, respectively.

Copley *et al.* (1944a) found that cover crops are of most value for erosion control in late winter and early spring and that the quantity of forage produced and method of seed bed preparation for a following row crop were factors affecting the ability of the cover crop to protect the land from erosion. Neal (1944) reported that a cover crop during the preceding winter reduced soil losses 50 per cent in New Jersey when the land was planted to tomatoes and sweet corn. Winter cover crops decreased cotton yields on two soils in central Oklahoma on land where water erosion is a serious problem during the summer, but is not a problem during the winter (Harper, 1939).

Vegetative cover in orchards is used to control erosion on sloping land. The problem of available nitrogen and moisture supply in relation to erosion control is important on a relative small acreage of land. Some of the orchard problems in Michigan have been described by Partridge (1937).

The Secretary of Agriculture in 1943 reported that soil-building crop rotations were needed on 212,000,000 acres of cultivated land in the United States. It is quite evident that farmers have been neglecting to improve their soils as well as to conserve them. When farmers do not adopt soil-building cropping systems to increase production it would not be logical to expect that they would make any change in cropping system to retard erosion. The big soil conservation problem on many northern farms is to increase the use of mechanical procedures and strip cropping on land where soil-building rotations are commonly used, and to reduce the acreage of row crops planted on moderate to steep slopes. In the southern and west-south central states where a high percentage of the farmers have used terracing and contour farming to retard erosion, soil-building crops have not been grown to maintain organic matter and a favorable structure for moisture absorption. Grasses that would not become pests and adapted legumes were not available for use in cropping systems with small grain until Korean and Kobe lespedeza were introduced about twenty-five years ago. Within recent years such plants as *Lespedeza sericea,* Alta fescue, rust-tolerant strains of oats, reseeding crimson clover, and other legumes have been used along with hairy vetch and rye to protect and build up the organic matter content of soil to reduce damage from run-off water on sloping land. No attempt has been made to grow crops which would improve soil fertility in the southern part of the Great Plains region. Better tillage methods and crop residue management offer greater opportunities for soil and water conservation than improved cropping systems in this area.

During the past fifteen years the Soil Conservation Service field staff has learned "What to do about cropping systems for soil conservation" and "How to do it" under a wide range of soil and climatic conditions. Work Unit Leaders in soil conservation districts are provided with a land classification map of each farm on which they are working, and recommendations can be made to limit the acreage of row crops such as corn or cotton on the steeper slopes. When a small farm has a wide variation in slope, which is often an indication of several different kinds of soil, it may be difficult to plan a cropping system that does not require an excessive investment in farm machinery. Two reasons why many farmers have continued to plant cotton and corn in preference to using a more diversified cropping system to control erosion has been the lower cost of machinery required to produce these crops and also the higher income obtained. A gradual shift from cash crops to grassland farming is occurring in some areas as the natural fertility of the soil declines because the cost of machinery required to plant and harvest small grain is high in relation to crop income.

The soil scientist, the agronomist, the engineer, the economist, and the soil conservationist must work together to solve the soil erosion problem. Row crops produce better yields than close-planted crops on soils which are low in natural fertility. On small subsistence farms it is not an easy problem to set up a soil-conserving cropping system which will also maintain farm income. The solution of this problem may not have much influence on total food production, but it could have an important effect on the social problem in many areas where farmers cling to the soil not from choice but because there are no new lands. Their hope lies beneath their feet.

### 3. *Terracing and Contour Farming*

The most common mechanical procedures for erosion control in many areas are terracing and contour farming. These practices are normally used together on slopes up to 12 or 15 per cent. Ramser (1917) accumulated data from field measurements on vertical spacing, ridge cross section and channel gradient for terraces which have served as a valuable guide to field practice. When the first Southwest Soil and Water Conservation Conference was held at College Station, Texas, in June, 1929, A. B. Conner, Director of the Texas Agricultural Experiment Station reported that 2,808,251 acres of Texas land had been terraced. Some of the earliest research information on the beneficial effects of terracing and contour farming was obtained near Spur, Texas, by Conner, Dickson, and Scoates (1930). After a rather exhaustive study of soil conservation practices for cotton production, Hendrickson (1949) concludes that no satisfactory substitute has been found for terraces and meadow outlets for the safe disposal of surplus run-off water.

More recent studies under a wide range of soil and climatic conditions have shown that the vertical spacing between terrace ridges can be much wider on moderately permeable soils than on slowly permeable soils having the same slope. When the gradient of a terrace channel is low, the ridge must be higher, especially near the outlet, to prevent topping during periods of excessive run-off. However, a low gradient has the advantage of reducing the volume of water to be handled at the terrace outlet and also reduces the loss of soil from a field. Hazen of the Oklahoma Agricultural Experiment Station made an extensive study of level terraces with open ends on sloping land and found that over a period of years, a channel gradient with a fall of about 0.1 per cent will eventually develop.

An improvement in terrace design, known as a channel type terrace, was made by Nichols (1937) in which all the earth is moved from the upper side of the ridge. This type of construction reduces the hazard from breaks caused by burrowing animals, if the bottom of the channel is maintained at a lower level than the normal slope of the land. This can be accomplished by leaving a dead furrow in the terrace channel when the land is plowed. Also the slope on the lower side of the ridge is not so steep or irregular as on a terrace where a considerable portion of the soil is moved up hill during construction. Consequently, it is easier to operate farm machinery over this type of terrace on moderate to steep slopes as compared with a method of construction which leaves a ditch on both the upper and lower side of the ridge.

Some data on terracing obtained on the Soil Conservation Experiment Station at Bethany, Missouri, by Smith *et al.* (1945) are as follows: Terracing was the most effective supporting conservation practice at the station principally because it reduced the length of the slope. Soil loss was only 2 per cent of that from an unterraced watershed. One-way plowing of terraced land in which the soil was turned up hill only partially compensated for down slope movement. Terracing increased the slope of the land from 7 to 9.2 per cent on one area, and from 12 to 17.6 per cent on another area. The cost of building a terrace ridge was 2.6 times as much on a 13 per cent slope as on a 7 per cent slope. A variable grade in the terrace channel was most satisfactory on this slowly permeable soil.

Experimental studies on Marshall silt loam near Clarinda, Iowa, as reported by Browning, Norton, McCall, and Bell (1948) indicate that terracing has given nearly complete control of soil and water losses. Contouring reduced soil losses from 27.2 to 5.2 tons of soil per acre and saved 2.5 in. of rain in one year. Level terraces were satisfactory on land with 6 to 9 in. of top soil where water could not be discharged at a terrace outlet without creating an erosion hazard on the lower slopes. Soil loss was less than 1 ton per acre at the terrace outlet when the channel grade was 6 in. per 100 ft. This gradient on most soils would greatly increase channel erosion. The maximum vertical interval between terrace ridges is about 9 ft. on this soil.

A report from the Blackland Soil Conservation Experiment Station near Temple, Texas, by Hill, Peevy, McCall, and Bell (1944) indicates that the vertical spacing of terraces should be 2.5 to 3.5 ft. on a 5 per cent slope to reduce soil loss on cultivated land. When the slope increased from 2 to 3 per cent, a much greater loss of soil occurred. Soil loss varied from 2.0 to 3.8 tons per acre annually from terraced land farmed on a contour. Terracing and contour cultivation with strip cropping are the most effective soil-conserving practices recommended for the Texas Black land area. Contouring alone did not protect cultivated land from severe soil loss during intense storms.

Data on terrace design for the Palouse region in the Pacific northwest presented by Horner, McCall, and Bell (1944) indicate that terracing is not practical when slopes exceed 15 per cent. Consequently, erosion must be controlled by other methods on much of the cultivated land in that area because it is too steep for terraces. The recommended gradient in a terrace channel varied from 1.6 in. per 100 ft. on a 4 per cent slope, to 6 in. per 100 ft. on a 15 per cent slope. Information on terracing at Zanesville, Ohio, also indicates that other procedures should be used to control soil erosion when cultivated slopes exceed 12 per cent, Borst, McCall, and Bell (1945). Terraces on a slope of 10 per cent lost 3.8 tons of soil per acre from the terrace outlet over a 9-year period, but down slope movement between the ridges was much greater than that amount.

A variable grade terrace used with contour farming and a rotation of cotton, oats, corn, or darso at the Red Plains Soil Conservation Experiment Station near Guthrie, Oklahoma, lost soil from the terrace outlets at the rate of 1 surface inch in 55 years. A combination of soil-conserving and soil-improving practices would permit this land to be farmed for several generations before any appreciable decrease in crop yield would occur. Down slope movement of soil on the terrace intervals which varied in slope from 3 to 5 per cent, combined with plowing to maintain the terrace ridges increased the depth of soil on the ridge and decreased the depth of soil between the ridges (Daniel, Elwell, and Cox, 1943). This effect could be partially eliminated with proper plowing.

Tobacco rows need more slope than most crops to provide adequate drainage when a system of ''contour'' tillage is used. A 1 per cent slope has been recommended by Copley, Britt, and Posey (1948).

The beneficial effect of contour farming on crop production as a result of water conservation has been reported by many investigators. Sauer (1949) obtained data on the average yield of several crops in Illinois from 1935 to 1945. Contouring increased corn yields 6.9 bushels, soybeans 2.7 bushels, oats 6.9 bushels, and wheat 3.4 bushels per acre. There was no significant difference in the labor, power, or machinery requirements to farm on the contour as compared with ordinary methods of farming.

Van Doren *et al.* (1948) reported that contouring increased yields of corn 2.9 bushels, oats 2.0 bushels, and soybeans 1.8 bushels per acre on a 2 per cent slope at Dixon Springs, Illinois, and saved 1.5 tons of soil per acre on corn land and 2.0 tons of soil per acre on soybean land.

Contouring in New York according to Lamb, Andrews, and Gustafson (1944) increased the yield of potatoes 15 bushels per acre on a 11 per cent slope, and soil losses were reduced from 14.0 tons to 0.1 ton per acre. Corn yields were increased 5 bushels per acre, and grape production was also increased by this practice. However, Gustafson, Lamb, and Wilson (1948) reported that potato yields were increased 10 per cent when planted on a contour during two dry years and decreased 9 per cent during 2 wet years as compared with rows parallel with a 4 per cent slope.

Browning (1948) states that contour listing of corn in Iowa reduced soil losses 50 per cent as compared with surface planting on plowed land. Over a 5-year period contour farming increased corn yields 7.3 bushels, soybeans, 2.7 bushels, and oats 5.4 bushels per acre.

Terracing and contour farming has been an effective method for water conservation on gently sloping land in the Great Plains area. Finnell (1934) found that level terraces produced 3.28 bushels more wheat over an eight-year period, 1926 to 1933, on land with a slope of less than 1 per cent as compared with wheat drilled parallel with the slope on adjacent areas. In a more recent study Finnell (1944) calculated the individual benefit from terracing and from contouring on wheat production. A combination of terracing and contour farming increased wheat yields 2.99 bushels per acre. The effect of contouring increased the yield 0.84 bushels and terracing 2.15 bushels per acre. Since the surface of wheat land is more nearly level as a result of tillage operations than land used for sorghums, the relative effect of contouring should be greater with sorghums than in the case of wheat where terracing had the higher value.

Contour planting of wheat over a 6-year period on the Wheatland Conservation Experiment Station near Cherokee, Oklahoma, produced 18.6 bushels per acre as compared with 17.6 bushels on adjacent land planted with the slope (Daniel, Elwell, and Cox, 1948). Wheat yields were lower during the first two years after the land was terraced than on unterraced land. After the effect of soil disturbance was corrected, wheat yields were increased 1.8 bushels per acre on the terraced land. No data on soil loss were obtained in these experiments.

Level terraces with closed ends can be used in subhumid areas on gently sloping land with a permeable subsoil to increase the efficiency of rainfall. However, on slowly permeable soils water collecting on the upper side of a level terrace during periods of excessive rainfall when wheat is growing on the land must be drained off to prevent injury to plant growth (Harper, 1941).

The effect of terracing and contour farming on the production of cotton was studied by Dickson *et al.* (1940) at Spur, Texas. Level terraces with closed ends increased cotton production 28 lb. of lint per acre over rows with a 5.5 per cent slope over the period 1927 to 1939. Cotton planted in rows parallel with a graded terrace having a uniform slope of 3 in. per 100 ft. produced only 18 lb. more lint than rows on a 5.5 per cent slope.

Terracing reduced the rate of run-off as compared with an unterraced area in Wisconsin from 10.75 to 4.5 cu. ft. per second (Hays and Palmer, 1936). This delaying influence on run-off should have a tendency to reduce flood hazards on small watersheds even though total run-off was reduced only about 2 per cent.

Jacks (Jacks and Whyte, 1939, p. 105) is of the opinion that at some future time the broad-base terrace may be regarded as the most enduring characteristic of twentieth century civilization.

### 4. *Grassed Waterways*

The development of water disposal systems to carry water from terrace outlets or contour strips to lower elevations is a relatively simple procedure under average conditions. When contour farming is practiced on an irregular topography, the natural drainage channels must be flattened, if necessary, and planted to a perennial grass to control or prevent gully erosion. The development of power lifts on farm machinery has made it easier for farmers to protect and maintain a grass waterway in a natural drainage channel. However, some farmers who appreciated the value of such a conservation procedure raised their plows by hand when crossing grass waterways many, many years before power lifts were made. When terraces are used to intercept run-off water on cultivated fields, grass waterways must be constructed where run-off cannot be discharged onto pasture or forest land.

A study of the protective value of different kinds of vegetation when subjected to varying quantities and velocities of run-off water has been made by several investigators. Cox and Palmer (1948) made a study of alfalfa, Bermuda grass, bluegrass, buffalo grass, weeping love grass, and a mixture of native grasses on slopes varying from 1 to 10 per cent near Stillwater, Oklahoma. Bermuda, buffalo, and bluegrama grasses can be used on 10 per cent slopes when the velocity of the run-off water does not exceed 7 ft. per second. Ree and Palmer (1949) made a comparison of Bermuda, Italian rye, centipede, Sudan, Dallis, and crab grasses, red top, common lespedeza, *Lespedeza sericea*, and Kudzu on channel slopes from 1 to 24 per cent on Cecil sandy loam soil near Spartanburg, North Carolina. Most of the channels were on slopes of 3 or 6 per cent. Bermuda and centipede grasses protected 10 and 20 per cent slopes when the water velocity was 8 ft. per second. Many of the other plants were satisfactory on slopes of 3 and 6 per cent when the water velocity did not exceed 5 ft. per second. Smith (1946) at McCredie, Missouri, studied the use of bluegrass and other grasses in grassed waterways and prepared a table showing the width required for different land areas on slopes varying from 1 to 16 per cent and water velocities from 1.1 to 4 ft. per second.

Under some conditions a pasture or meadow strip should be planted on one side of a field where a uniform slope is available so that the run-off water can be spread over much of the grass land by carrying the upper terrace nearly across the grassed strip and shortening each lower terrace slightly so that water from each outlet will flow over a different part of the grassed area. Wide strips of grass are superior to narrow strips on soils containing a high per cent of plastic clay. Cracks which develop in such soils on drying weaken the stability of grass waterways when a large volume of water flows over the surface.

Gully direction has been changed in many fields where water from terrace outlets was discharged over a bank into a road ditch, causing an over fall which gradually moved up the terrace channel. Grassed waterways must be used to prevent the reoccurrence of such problems.

### 5. *Infiltration and Run-off*

A large number of experiments have been conducted to collect information on the infiltration of rainfall and run-off under varying soil and climatic conditions. An inverse relationship normally occurs between these two processes unless rainfall intensity is very high. Many factors affect the rate of water absorption by a soil, such as surface cover, moisture content, roughness of the surface, slope, stability of soil aggregates, rainfall intensity, surface texture, and type of clay mineral present. However, a few intense rains are responsible for much of the run-off and most of the erosion that occurs.

Many individuals have a direct or indirect interest in the various factors which increase or decrease the infiltration of rainfall. The engineer is interested as it relates to flood hazards, the geologist to the ground water supply, and the agriculturist as it may increase or decrease crop yields where moisture is a limiting factor in plant development.

Data collected in Missouri by Duley and Miller (1923) and in many other experimental studies have shown that the highest run-off occurs on bare soil. A four-year study by Alderfer and Merkle (1944) indicates that protective cover, rather than change in soil structure is responsible for the increased infiltration of rain.

Loss of soil organic matter as a result of the continued production of soil-depleting crops greatly increases the need of mechanical procedures to hold water on the land for a longer period of time, so that it can be absorbed by the soil. Several investigators have reported that silt and clay in run-off water fills the larger pore spaces at the surface of the ground and retards the rate of infiltration (Hendrickson, 1934; Horton, 1933).

Ellison (1944, 1947) has measured the kinetic energy of raindrops and their disintegrating effect on soil aggregates, which makes the dispersed silt and clay particles more easily transported by run-off water. One rain falling on an easily detachable soil may splash more than 100 tons of soil into the air on open fields. Uhland (1947) reported that soil aggregates taken from land cropped annually to corn were completely dispersed by approximately 6 raindrops falling on them from a height of 30 cm. Whereas, the average number of raindrops required to disperse soil aggregates from land that had been in a meadow one year was 37.7, in a meadow two years, 41.2, and in alfalfa 13 years, 40.2.

Duley and Kelly (1939) found a compact layer about 3 mm. thick on the surface of soil where torrential rains fell on bare land, and this layer retarded the absorption of water, although the macroscopic pore space in the soil immediately below the layer was favorable for rapid moisture movement. A straw mulch prevented the formation of this compact layer and increased the absorption of water from 0.24 in. per hour on bare soil to 0.74 in. per hour on mulched land. The moisture content of the soil on which these experiments were conducted was less important than surface cover on the rate of infiltration. Peele (1945) found that beating rains formed an impervious layer on sandy loams quicker than on clay loams in cultivated areas.

Borst *et al.* (1945) found that the infiltration rate was not constant for the same soil during different periods of the year. It was lower in the winter-early spring period than during the summer. Frozen soil was relatively impermeable to water. Run-off from land in soybeans was measured on slopes of 4.2, 9.3, 15.3, and 22.5 per cent. The percentage of water lost varied from 59.8 per cent on minimum slopes to 75.8 per cent on maximum slopes when water was applied from a sprinkler system at the rate of 4 in. per hour. Run-off according to data obtained by Duley and Hayes (1932) increased on slopes up to 3 per cent, but a further increase in slope had little effect on run-off.

Soil variations are quite likely to cause differences in the rate and quantity of water absorbed within the same area as well as in different regions. Copley *et al.* (1944a) measured the rate of run-off on burned and unburned forest land on a 10 per cent slope. The average annual loss of water from the unburned area was 0.026 in., whereas 5.38 in. was lost from the burned areas, when the average annual rainfall was 46.47 in. The water loss from the burned area was slightly lower than values obtained on continuous cotton under similar conditions. Water losses from burned and unburned forest land at the Red Plains Conservation Station near Guthrie, Oklahoma, reported by Daniel *et al.* (1943) show that the average annual loss of water from unburned forested land with a 5 per cent slope was 0.036 in., whereas the loss from burned land was 1.14 in. when total rainfall was 30.57 in. per year. Run-off from cotton land on a 7.7 per cent slope was nearly 3 times as high as from the burned forest. The maximum water loss during any one year was about 10 per cent of the annual rainfall on the burned forest area. Overgrazing and fire on mountainous areas have increased soil erosion and flood hazards in Utah (Bailey, Forsling, and Becraft, 1934).

Since 130,000,000 acres of forest land are found on farms, the management of this land must be considered in some areas in the development of a soil conservation program. However, conservation logging and soil conservation are two different problems. Since the grazing value of forest land is low, the most important treatment for soil and water conservation on this type of land is fire protection to conserve water and to protect the trees if they have any value. Merely cutting a forest does not destroy the ground cover. Fire protection, according to Shepard (1928), will permit rapid revegetation in most areas.

Duley and Russel (1942b) found that moisture storage in the soil to a depth of 6 ft. under plowed land was increased from 3.71 to 9.72 in. of water during a season of abundant rainfall where two tons of straw was placed on the surface after plowing. During two dry seasons 1.96 in. more water was stored in the soil under the straw mulch as compared with a plowed, unmulched area. (Duley and Domingo, 1949) also conducted infiltration studies on pasture land and reported that the total cover of grass and litter was more important than kind of grass on water absorption. When the dead plant residue was removed from an area where only a thin stand of grass was present in a pasture, water intake was reduced from 1.55 to 0.50 in. per hour. Water infiltration was very similar on grassland whether the slope was 5 or 15 per cent. Rain falling at the rate of 3 in. per hour caused little loss of soil on grassland, on soil protected by a straw mulch, or on wheat stubble where the crop had been threshed with a combine.

Musgrave and Norton (1937) reported that Marshall silt loam, an important soil in western Iowa and northwest Missouri, absorbed rainfall from 7 to 10 times as rapidly as Shelby silt loam which has a more dense subsoil. Treatment which impounded 2.5 in. of water on level land only retained one-fourth as much water on a 15 per cent slope.

Borst and Woodburn (1942) covered a 5 per cent slope with 2 tons of straw per acre, nine weeks before applying artificial rain, and found that 97.5 per cent of the water was absorbed by the straw covered soil, whereas unmulched plots absorbed 92 per cent of the water. Although the difference in water absorption was not great, the soil loss from the mulched plot was only a few pounds per acre, whereas the bare plot lost soil at the rate of 10 tons per acre.

Farm ponds have been emphasized by soil conservationists as a part of a soil conservation program, whereas they are normally used as a water supply for livestock. Zingg (1946) studied the value of farm ponds for flood control on a watershed in Missouri and concluded that the beneficial effect was less than 1 per cent.

Watershed treatment to reduce soil erosion and run-off was authorized on eleven watersheds by the Federal Flood Control Act of 1944. At the present time the Soil Conservation Service is working on the Washita River watershed in Oklahoma to determine to what extent a combination of mechanical procedures and improved cropping systems combined with revegetation of shallow soils will have on flood control. Twenty-four small flood control reservoirs have been built and soil-conserving practices have been established on 65 per cent of the Sandstone Creek watershed. It may be several years before a big rain will fall on this watershed. The Secretary of Agriculture reported in 1942 that flood damage in this valley was $2,300,000 annually. Benefits derived from erosion control treatment should reduce the annual flood damage about $407,000 according to estimates prepared by the Soil Conservation Service. Rate and quantity of rain have an important influence on various procedures which are needed to control erosion under different soil conditions. Some data on this subject have been compiled by Blumenstock (1939).

Soil erosion on land owned by the federal government can be protected by political action. On privately owned land the problem of economics may often influence the extent to which individual cooperation may be obtained. Where soil conserving practices are applied to all of the land within a watershed, increased infiltration should have a reducing effect on stream flow. However, when rains of 10 to 14 in. occur on a soil already moistened by previous rainfall, the percentage of run-off will be high, and erosion control measures will have little influence on big floods that may cause severe damage to crops, rural improvements or cities which were unwisely located on the flood plains of streams. Silting of stream channels will increase the damage from small floods, but it has no influence on the effect of large floods which often cover both the normal flood plain and second bottom land where these areas are not protected by a levee.

Farmers on unprotected bottomland are gambling with floods just as farmers on the upland are gambling with drought. They plant crops hoping that floods will not occur. In many southern areas where a crop is destroyed by a spring flood, a summer crop will be planted to obtain some income from the land. A good pasture on bottomland where floods often damage cultivated crops, will often produce as much income from livestock as will be obtained from cultivated crops. Using bottomland so that much of the flood damage to cultivated crops can be avoided is a more economical solution for the flood problem in many areas than to construct a big dam which does not protect land above the reservoir from floods, covers many acres of productive bottomland with water and often provides only limited protection to a few farms downstream. More information is needed on the relative income from different systems of farming on bottomland affected by floods, since shifts in farming procedure would not only be more permanent and certainly less expensive than flood control by means of dams, which are relatively temporary in the life of a nation, and over a period of years are nothing but gigantic silt catchers in the channels of streams.

A more complete review of physical soil factors which affect water absorption and run-off will be found in a textbook by Baver (1940) and in papers listed under Sections 1 and 6 of the *Soil Science Society of America, Proceedings* (1936-1949).

### 6. *Crop Residue Management*

Many studies have been conducted to compare the effect of plowing on soil loss and crop production with other methods of tillage which leave a considerable portion of the crop residue on or near the surface of the ground. Sweeps, chisels, one-way disks, the Noble blade, and other tools have been used for subsurface tillage on wheat land in the

Great Plains and in the Palouse area of the Pacific northwest to control wind erosion or reduce soil loss from run-off water. Conserving rainfall to produce more crop residue as well as increase crop yields may be an important part of crop residue management for erosion control during many seasons in a low rainfall area.

Experiments on the effect of subsurface tillage which left the straw on or near the surface of the ground near Amarillo, Texas, produced an average yield of 11.4 bushels of wheat per acre as compared with an 8.6-bushel yield on plowed and disked land (Merrill, 1947).

McKay and Moss (1944) studied wheat production and soil loss in Idaho on land subtilled with a lister bottom which left 94.5 per cent of the straw on the surface, and on adjacent areas turned with a moldboard plow. The slope varied from 15 to 20 per cent, and the straw yield was 4,500 lb. per acre. Soil loss on the subtilled plot was 2 tons and on the plowed plot 8.7 tons per acre. Crop yields for the period 1940-1943 were 34.6 bushels on the subtilled and 31.6 bushels per acre on the plowed land. Daniel, Elwell, and Cox (1948) reported that winter wheat near Cherokee, Oklahoma, produced an average yield of 15 bushels on subsurface tilled and 19.9 bushels per acre on plowed land in one experiment from 1942-1947, and in another study on a rotated watershed the yield on subsurface tilled plots was 17.8 bushels, and on land one-way disked 19.7 bushels per acre. Insect damage and weed competition were partly responsible for the lower yield on the subsurface tilled plots.

The effect of different methods of tillage on wheat production and moisture conservation in Montana was reported by Aasheim (1949). A six-year study near Froid on Lihen sandy loam using several methods of tillage indicated that wheat yields were as high on land where subsurface tillage was used as on plowed plots. Soil loss from water and wind erosion was much lower on the subsurface tilled areas. Similar results were obtained in a five-year study near Havre.

Worzella *et al.* (1948) reported that both corn and wheat yields were slightly lower when subsurface tillage was used after the wheat was combined as compared with plowing the land. Also, wheat yields were decreased immediately after a grass sod.

Extensive studies at the Dry Land Field Stations in the southern part of the Great Plains area have shown that stirring the soil as soon as possible after harvest is more important than method of tillage on wheat production. Throckmorton (1942) reviewed the wheat yields obtained from burning, plowing, partial incorporation of straw in the surface soil and subsurface tillage on a large number of experiments and found that yield differences were usually in fractions of a bushel with a slight advantage usually in favor of burning the straw and plowing.

In the northern part of the Great Plains area, weed control is a problem following subsurface tillage when wheat is planted every year. Spraying with 2-4,D to control weeds on subsurface tilled plots may be a solution for this problem.

The use of the one-way disk expanded rapidly in the wheat belt from 1925 to 1930. This tool will leave a part of the straw on the surface of the ground, although different designs and sizes of disks combined with depth of operation and rate of travel produce different results. When drought years reduced the production of wheat in the Great Plains area from 1930 to 1934, farmers continued to stir their land and the active organic matter disappeared. Severe dust storms reached a maximum in 1935 when nearly one million acres of land in Kansas was affected by wind erosion (Throckmorton and Compton, 1937). Developing a cloddy surface where possible by deep listing is about the only method of controlling soil movement on land which has no undecomposed or partially decomposed vegetation on the surface of the land. Finnell and Daniel (1939) are of the opinion that severe damage from wind erosion is not likely to occur if tillage methods are used which leave most of the crop residue on or near the surface of the land, unless drought should cause a crop failure for three consecutive years. Under such conditions the quantity of partially decomposed crop residue will decrease to a point where wind erosion may become a serious problem on sandy or silty soils. If sorghum is planted on land where a protective cover has disappeared because of the gradual decomposition or disintegration of previous crop residues, sufficient forage will normally be obtained from summer rainfall to protect the land from wind erosion. Adapting cropping procedure to soil moisture conditions is an important part of a successful farming program in the Great Plains area.

An attempt to use subsurface tillage under a humid environment has created many problems which do not exist in the wheat belt where grass and weeds are easily killed during hot dry weather when the roots are cut and the surface soil is loosened with a sweep operating 2 or 3 in. below the surface of the ground.

Nutt and Peele (1947) compared three methods of mulch tillage on Cecil sandy loam in South Carolina on an area where rye and vetch or crimson clover were planted in cornstalks in the fall. These methods were as follows: (1) the mulch balk method, (2) the mulch disk method, and (3) plowed and clean cultivation. Similar yields of corn were obtained from all treatments. The important benefit derived from subsurface tillage was that soil losses were only 17 and 54 per cent as great as on the plowed land.

Duley and Russel (1941) studied the effect of straw and cornstalk residues left on the surface as compared with plowing them into the soil on corn yields. About the same yield was obtained where corn followed corn. Yields were increased about 3 bushels per acre where wheat straw was left on the surface. These authors (1942a,b) also studied the effect of straw and cornstalk cover on soil loss from summer fallow plots which received 7.12 in. of water in 8 rains and found that 2.2 and 2.79 tons of soil per acre were carried, respectively, from the straw and cornstalk mulched plots, whereas 16.39 tons of soil was removed from a plot where the straw was disked into the surface soil. The average loss for three years from summer fallow land was 6.24 tons of soil per acre where 2 tons of straw per acre was disked into the soil, and 0.97 tons of soil from a plot treated with straw where the land was subsurface tilled. These same authors (Duley and Russel, 1949) compiled some average yields of corn following corn, wheat, and oats under Nebraska conditions which are as follows:

| | | Corn Average Yield, Bushels per Acre | |
|---|---|---|---|
| | | Preceding Crop plowed under | Residue on surface, subsurface tillage |
| Corn | 1939-41 (3 dry years) | 18.7 | 31.1 |
| Corn | 1942-44 (3 wet years) | 73.7 | 62.2 |
| Wheat | 1939-44 | 28.1 | 26.7 |
| Oats | 1940-45 | 51.2 | 48.1 |

Browning and Norton (1947) found that plowing was superior to subsurface tillage for corn production in Iowa. Fifty-two trials on eleven soil types over a three-year period averaged 70.8 bushels per acre on plowed land and 63.6 bushels per acre on subsurface tilled fields.

Van Doren and Stauffer (1944) applied 2 tons of straw per acre to corn land after planting in Illinois, and this treatment decreased corn yields over a three-year period from 92.7 to 76.5 bushels per acre, but increased soybean yields from 29.2 to 31.5 bushels per acre. Free *et al.* (1946) reported that corn in New York produced 54.9 bushels per acre on plowed land, 40.8 bushels on subsurface tilled plots, and 28.8 bushels on disked plots. When trash was left on the surface, the stand of corn was poorer and weed control was more difficult than on the plowed plot.

Helm (1940) reports that under Missouri conditions Korean lespedeza does best in small grain when the legume residue from the previous season's growth is worked with a field cultivator equipped with narrow shovels or sweeps before the small grain is planted. When small grain and lespedeza were grown on the land each year, soil loss was similar to that occurring in a three-year rotation of corn, small grain, and a grass-clover mixture (Smith *et al.*, 1948).

### 7. *Soil Loss and Land Use*

Crop yields decline when erosion of soil from crop land underlaid by weathered igneous, sedimentary, or metamorphic rock exceeds the rate of soil formation. If nothing is done to control erosion when row crops are planted on steep slopes, only a few crops may be produced in a torrential rainfall area before the land will be abandoned because of physical soil deterioration.

Too little erosion on some land caused the development of an impervious subsurface horizon due to the downward movement and accumulation of clay. A soil of this type is called a planosol. Although it is an old soil, it has been changed to a shallow soil on a gentle slope. Loss of soil from this type of land is more serious than on soil which has a more permeable subsoil, because any decrease in the water-holding capacity of the surface layer will increase the drought hazard, especially for summer crops.

Many cropping systems for erosion control will be difficult to evaluate unless more research can be conducted over a long period of time under different soil and climatic conditions. Several investigators have studied this problem and have suggested rates at which soil could be removed from a field by sheet erosion without causing serious damage to the land.

Not only the quantity of soil lost, but also its chemical composition may be important. Neal (1944) found in New Jersey that sediment removed from land by run-off contained about half as much sand, 4 times as much organic matter, 3.1 times as much phosphoric acid, and 1.4 times as much potash as was present in the field soil. Whitson and Dunnewald (1916) reported many years earlier that three times as much nitrogen and twice as much phosphorus were in the sediment removed from an adjacent slope as in the soil which had not been sorted by run-off water.

Smith, Whitt, and Miller (1948) are of the opinion that the maximum annual soil loss per acre in Missouri on the Marshall series is 4 tons, claypan soil 3 tons, and Ozark region soils 2 tons per acre. The use of cover crops and some kind of soil-improving crop or practice is an important factor in keeping soil loss below the maximum value that can occur without causing serious injury to the soil, at least for a long period of time. Planting rye in cornstalks in the fall reduced soil loss from soybeans planted the following year from 7 to 3.5 tons per acre. Soil losses on corn land were reduced from 8 tons per acre following lespedeza to approximately 2 tons per acre following a grass-legume sod. These investigators concluded that not more than half the land should be in row crops on Putnam silt loam with a slope of 3 per cent. Erosion on small grain land was reduced 50 per cent by fertilization. A wheat-clover hay cropping system reduced losses to less than 2 tons per acre. Corn yields were decreased 4 bushels and soybeans 1.6 bushels per acre for every inch of soil lost from Shelby, Grundy, and Putnam soils.

Soil loss on deep loess or alluvium is less harmful than on other types of land. Musgrave and Norton (1937) produced 80 bushels of corn per acre after sweet clover had been grown on Marshall silt loam in Iowa where 12 in. of the top soil had been removed. Browning *et al.* (1947) recommend that soil loss should not exceed 2 to 6 tons per acre in Iowa, depending on the soil type. The soil-conserving value of a meadow sod disappeared in two or three years after the sod was plowed.

Rockie and McGrew (1932) found that soil loss was very low (1) in alfalfa fields, (2) in a pasture with a thin stand of bunch grass, and (3) on grain fields in Washington from storms which caused severe erosion on fallow land. The most important problem in that area is to protect fallow from erosion.

Hays and Clark (1941) recommended that cropping systems which keep annual soil losses below 3 tons per acre should be used in Wisconsin. This can only be accomplished by using the steeper slopes for meadow or pasture. Fayette silt loam lost 0.3 ton of soil per year from a 16 per cent slope producing alfalfa-timothy hay, whereas, soil loss was 8 tons per year in a rotation of corn, barley, and three years of hay. Soil losses from barley on 3, 8, 13, and 16 per cent slopes were 0.69, 2.34, 6.8, and 17.19 tons of soil per acre. Cropping systems which would reduce soil loss to 3 tons per acre on moderately eroded slopes were (1) corn, barley, and hay, or (2) corn, corn, barley, and three years of hay. Four years of hay is recommended in a corn-barley rotation on a 9 per cent slope, and 6 years of hay or pasture with corn and barley on a 12 per cent slope. Barley produced 42 bushels per acre on a soil 9 in. deep, 26 bushels when the soil was 5 to 6 in. deep, and 16 bushels on land with 3 in. of top soil.

The average annual soil loss on a 3 per cent slope planted in cotton each year was 3.5 tons per acre on Cecil sandy loam at Watkinsville, Georgia. Soil loss on a 7 per cent slope was 5.95 tons per acre when cotton was grown in a rotation and 20.65 tons per acre when cotton was planted every year (Carreker and Barnett, 1949).

It is quite evident from the above data and from other erosion studies on crop land that the acreage of row crops on sloping land must be decreased so that soil losses from erosion will not exceed the rate of soil formation. The classification of land according to erosion susceptibility as described by Hockensmith and Steele (1943) is an excellent guide in the development of cropping systems to prevent serious erosion. Any system of management which permits a greater loss of soil from cultivated land than the rate at which weathering process will form new soil on the subsurface layers will eventually force a change in land use. Joffe (1949) has presented information from Russia to show that the rate of soil formation on old fortresses constructed of limestone or calcareous material varied from 20 to 220 years per inch of soil material produced.

The character of the rock, climatic conditions, and vegetative cover are important factors affecting the rate of rock weathering. It is quite probable that soil loss from erosion on sloping cultivated land would greatly exceed the rate of soil formation on very pure limestone, on granite formations, or on sandstones strongly cemented with iron or silica. However, on weakly cemented sedimentary rocks, impure limestones, or sediments of alluvial or glacial origin, the rate of soil loss could easily be reduced below the rate of soil formation.

Thousands of acres of shallow soil on moderate to steep slopes which were formerly used for the production of row crops were quickly damaged by erosion before farm operators realized what was happening to the land. However, much of this land can be converted to a high-producing pasture under favorable economic conditions. Deeper soils in humid areas usually require the use of soil-improving practices, such as the use of legume rotations, fertilizer, and lime to maintain or increase crop yields, before their physical value is seriously impaired by soil loss. This treatment will help to retard excessive erosion until the landowners or operators learn that one or more soil-conserving practices must also be used to protect the land from excessive soil losses.

The use of mechanical or vegetative procedures to retard run-off water combined with soil-improving practices will solve the erosion problem on most cultivated fields. Experimental data show that row crops must be planted at less frequent intervals or be completely eliminated from cropping systems on steep slopes to conserve the soil. The important problem is to convince the farmer that a cropping system must be changed under such conditions to prevent the physical value of the soil from deteriorating to a point where it will eventually become unsuited for the continued production of cultivated crops.

### 8. *Pastures*

Soil conservation is not an important problem on several hundred million acres of grassland in the United States. When pastures or ranges are stocked on the basis of favorable seasons, grazing problems will be encountered during periods of drought. Over-grazing will reduce the carrying capacity of a pasture under such conditions, but it does not seriously increase the erosion problem except that increased run-off may cause gully erosion, especially in semi-arid hilly or mountainous areas. Reducing the number of livestock 50 per cent in northwest New Mexico doubled the gain and improved the range (Hubbard, Thompson, and Gardner, 1944). Studies by Whitman, Hanson, and Peterson (1943) in North Dakota revealed that grassland cover deteriorated from 53 to 67 per cent because of the severe drought of 1932 to 1937, but during subsequent years when seasonal rainfall became more favorable, the grass cover was just as dense as before the drought occurred.

Borst *et al.* (1945) made a study of soil losses on unfertilized pasture land near Zanesville, Ohio, and found that annual soil loss on a steep slope was only a few hundred pounds per acre, whereas, several tons of soil were eroded from a similar area of cultivated land. Kelly and Midgley (1947) measured the soil loss from a bluegrass-white clover pasture on a 16 per cent slope in Vermont and found that 37 lb. of soil was removed per acre per year from an unfertilized area. If soil loss continued at this rate, it would require 400,000 years to remove 6 in. of surface soil. Similar results were obtained in Nebraska by Duley and Russel (1942b). Soil losses from plots planted to grasses, legumes, or grass-legume mixtures on steep slopes at all the Federal Soil Conservation Experiment Stations have been very low. Even during the "dust bowl" period from 1934 to 1936 very little damage occurred to the soil from wind erosion on grazing land in the Great Plains area except on very loose sandy areas, or where the grass was smothered by a thick layer of earth blown from adjacent cultivated fields.

Grazing studies in Wisconsin revealed that cattle on a good pasture consumed about 50 per cent of the grass on a 39 per cent slope and 85 per cent of the grass when the slope was less than 20 per cent. When pastures are not overstocked, the grazing habits of cattle tend to protect the steeper slopes (Ahlgren *et al.*, 1943). A system of pasture rental based on seasonal grazing per steer which tends to prevent over-grazing was described by Nelson (1945).

Pastures are a product of nature in a grassland region, whereas elsewhere they must be planted on land formerly covered with forest. Several million acres of formerly cultivated land make up a considerable portion of the pasture land on many farms. However, most of this land is protected by some kind of a vegetative cover, and erosion is not a serious problem except in gullied areas or where sheet erosion removed most of the surface soil before cropping was discontinued.

Contour furrows have been used on pasture land principally to catch run-off and to increase the moisture content of the soil in a localized area. Methods of tillage which will hold rainfall in a depression until it can be absorbed by the soil have more value under low rainfall conditions than in a humid region, especially as an aid in the reseeding of an area. Some beneficial effects from furrowing a Buffalo grass pasture were reported by Dickson, Langley, and Fisher (1940) at Spur, Texas. Yields of forage were increased from 654 lb. per acre on untreated land to 2,132 lb. per acre on the furrowed pasture. Root growth was increased from 2.0 to 3.7 tons per acre, 66 in. deep, and basal cover increased from 14.0 to 64.9 per cent. An increase in the availability of soil nitrogen as a result of tillage may have been partly responsible for the improvement and the growth of the Buffalo grass in this study.

When pasture lands are not over-grazed, contour furrows are not needed to conserve water or to protect the soil from erosion. Terraces are not required in a pasture improvement program except to prevent water from flowing into gullied areas when a new pasture is being developed on formerly cultivated land.

The fertilization and reseeding of idle or abandoned land with pasture grasses and/or legumes to improve its grazing value is an important method of increasing farm income. Many farmers in the southern states have converted both crop and idle land to pasture during the past twenty-five years, and interest in soil conservation was not the principal reason for this change. Boll weevil became a serious problem in much of the cotton belt about 1923. Prior to that time Johnson and Bermuda grass had gradually been spreading in many fields. Row crops such as corn and cotton which grow during the summer months favored the spread of these pests. Tillage and weed control problems were increasing, especially on fine-textured soils during seasons of excessive rainfall. Consequently, beef and dairy production has been increasing in the southern states because it provided a less hazardous type of agriculture than cotton and corn. Buie (1947) reported that nearly eight million acres of formerly cropped land in the southeastern part of the United States were not being cultivated in 1945. Reclamation is the important job on this type of land. Consequently, good agronomic practices which improve the grazing value of pasture forage, such as fertilization, liming and reseeding, or the control of over-grazing, are a much more important part of good grassland management than practices which have as their specific objective the control of soil erosion or the conservation of rainfall.

An important part of soil conservation research and field operations in some areas has included such agronomic activities as brush and weed control, fertilization and liming, and reseeding of pastures. Since such activities are not problems of soil conservation, they are apparently conducted on the premise of a more economic use of land. The Production and Marketing Administration of the U.S. Department of Agriculture also has included in its agricultural conservation program many pasture improvement practices which are used primarily to increase forage production either (1) through soil improvement, (2) reducing grass competition by destroying weeds and brush, or (3) reseeding to improve the grazing value of pasture land where the percentage cover of climax species has been greatly reduced by over-grazing or drought.

Pasture improvement in a humid region is an important problem because the vigor of a grass cover tends to decline with the disappearance of legumes where they can be grown in a grass-legume mixture. The soil conservationist has provided some helpful information on this phase of the pasture management problem by studying soil losses when different methods of tillage have been used on sod-bound pastures, such as disking, shallow plowing, or chiselling, to stir the surface sufficiently so that soil-improving practices can be applied and soil losses can be kept at a minimum while a new turf is being established.

On most pasture land, when desirable types of forage disappear as a result of over-grazing or drought, much of the vacant soil space will be covered within a short period of time by annuals or perennials which are often less desirable types of forage than the original vegetative cover. These pastures will have a lower grazing value than under virgin conditions, but erosion is not a serious problem because pasture herbage grows during the spring and summer and provides protection to the land when torrential rains are most likely to occur.

The interest of the soil conservationist in the economics of good grassland management is easily understood when a comparison is made of livestock production on poorly managed grassland and well-managed grassland. Farm income is often reduced while a soil conservation program is being established on cultivated land, consequently the conservationist who is quite anxious for his program to succeed may recommend a pasture-fertility program to increase farm income. Since soil improvement to increase forage production and the grazing value of a pasture will indirectly increase the absorption of rainfall and slightly reduce soil loss, soil and water conservation would be one of the indirect benefits of good pasture management, but it is relatively unimportant in a pasture improvement program under average conditions.

The big pasture job for the soil conservationist is to convince more farmers that cultivated land on steep slopes or on shallow soils should be changed to permanent pasture or meadow before the physical character of the land deteriorates to a point where it will be more difficult and expensive to make such a shift in land use. This is the important part of the pasture problem that falls within the realm of a soil conservation program.

### 9. *Strip Cropping*

Strip cropping is a useful method for controlling water or wind erosion on fertile soils in areas of low rainfall intensity. Kell and Brown (1937) described three types of strip cropping which may be used under different soil and climatic conditions. Contour strip cropping is adapted to slopes which are not too irregular and are too steep to terrace. The method may also be used on gently sloping permeable soils. Normally the strips should be narrower than a terrace interval under the same conditions. Where the surface topography is irregular, field strips combined with grassed waterways can be used, in which the row direction of the crop in the strips may vary from a contour by 1 per cent on gentle slopes and 2 per cent on moderate slopes. Wind stripping is used principally to prevent excessive soil movement on sandy soil or fallow land.

Bennett (1935), in his report to the Secretary of Agriculture, described the importance of strip cropping on seven watershed demonstration areas. Strip cropping was planned for 90 per cent of the cultivated land on cooperators' farms. In the Stillwater Creek and Pecan Creek watersheds in Oklahoma strip cropping was planned for 91 and 77 per cent of the land, respectively. The practice was discontinued in these areas as soon as the Soil Conservation Service contracts expired. Contouring which was used on some farms before the watershed programs were started has increased to some extent along with an increase in terrace construction.

Walter (1938) reported that most of the change in land use in the Crooked Creek area of Pennsylvania, as recommended by Soil Conservation Service technicians, was the rearrangement of field boundaries to establish contour strip farming. The average number of fields per farm was increased from 13 to 21 and the average size decreased from 4.5 to 2.7 acres. Most of the farms studied were larger than the average for the area. Very few of the farmers used enough lime to produce a good growth of legumes and only 38 per cent of the small grain acreage was fertilized in 1934. Strip cropping is of little value in controlling erosion on sloping land when soils are poor.

Research on strip cropping has been conducted in many states. Studies by Diseker and Yoder (1936) show that strip cropping in Alabama should supplement terraces rather than replace them. Strips of sod and small grain crops stopped the sand but did not filter out the silt and clay.

Studies at Bethany, Missouri, by Smith *et al.* (1945) indicate that successful strip cropping requires a fertile soil, a convex slope, well-grassed waterways, and a slope of limited length. The migration of chinch bugs from small grain into corn which is normally grown in the crop rotation and the difficulty of grazing the strips with livestock until all the crops are harvested make strip cropping impractical in this vicinity.

The use of strip cropping on black clay soils in Texas did not protect the land from gully erosion when oats were planted in strips 36 ft. wide. The strip cropped area lost 6.5 tons of soil per acre as compared with 3.8 tons per acre from a terraced area. However, strip cropping with terraces is recommended (Hill *et al.*, 1944).

Strip cropping on Iowa farms is not recommended because of insect problems such as grasshoppers and chinch bugs and greater damage to the corn crop from hot winds. Favorable results from strip cropping in New York have been reported by Free *et al.* (1946). Strips 72 ft. wide are recommended on 16 per cent slopes. The width of the strips should be increased as the slope decreases.

At La Crosse, Wisconsin, contour strip cropping with a good rotation in which a sod crop remains on the land for two to four years is one of the best procedures for the control of erosion. Heavy losses of soil occur when corn or small grain occupies the strip at the foot of a slope because strip cropping does not greatly reduce run-off and the total volume of run-off water increases on the lower part of a slope. Row crops cannot be planted on slopes above 15 per cent without excessive loss of soil (Hays *et al.*, 1949).

Strip cropping has been used to some extent in the Great Plains area to conserve rainfall and protect fallow land from wind erosion (Coles and Morgan, 1938). When small grain is planted on a contour, every row will help to retard the lateral movement of run-off water after the plants are established. Consequently, contour strip cropping with fallow in a low rainfall area will increase crop production. Mulch tillage, however, is a more popular practice.

When contour strip cropping is used on irregular slopes, some conservationists have proposed that the row crop be planted in strips of equal width to avoid point rows, and that the irregular strips be planted to small grain or hay. Maintaining soil fertility would be a difficult problem if such a procedure were followed.

Wind stripping with sorghum and cotton on sandy land in the Southern Great Plains area has not been a popular procedure. One reason for this condition may be that these crops are usually planted in late spring after the most serious period for wind erosion is over. When peanuts are planted between strips of sorghum on sandy land, the sand will drift from the area where the peanuts were grown into the sorghum stalks and produce an undulating topography.

### *10. Shelter Belts*

Shelter belts of trees, shrubs, and tall growing annuals are often used to control soil blowing and protect valuable crops from strong winds. A field shelter belt program was started in the Great Plains area in 1934 for the purpose of protecting cultivated land against wind erosion. It was one of the New Deal Action programs initiated at a time when unemployment, drought, and dust storms were serious problems in that area. The first trees were planted in 1935, and a total of 18,510 miles were planted from North Dakota to Texas. A good growth of trees was obtained on deep, coarse, or medium-textured soils, and an excellent growth was produced on a few areas of subirrigated land. One important criticism of the shelter belt program was that the trees were planted east of the area where wind erosion was most severe. A second problem associated with shelter belt planting is that no immediate income or very little future income will be obtained from the land occupied by the trees or the area occupied by tree roots which often extends several rods beyond the last tree row into adjacent cultivated fields.

Many of the trees planted in these shelter belts are not suitable for posts, and much of the land is too valuable to be used for the production of fire wood. No beneficial effect of birds on the control of insects has been observed when greenbugs, grasshoppers, leafhoppers, leaf worms, and other crop pests have appeared in large numbers. Also very few data have been collected in this area to measure the effect of reduced wind velocity on the leeward and the windward side of a shelter belt on increased crop production. Stoeckeler and Williams (1949) report some data from Texas and Oklahoma where cotton yields were increased 7.9 per cent at a distance of 10 to 20 rods from the tree belt. This increase would fall far short of compensating for loss of income from the area occupied by the trees. Most of the shelter belt trees were planted along section or half-section lines, and the tree strips are normally at least 320 rods apart. In some areas these belts may occupy low ground on rolling land and provide little protection to higher portions of adjacent fields. Some of the shelter belts were planted on soil unfavorable for trees, or were given poor care during the initial stages of growth. Consequently, crops on adjacent fields received little protection from the wind. In some instances, farmers have removed good shelter belts with bulldozers after their contract with the federal government expired and are cultivating the land. It is doubtful if many farmers would plant a field shelter belt in the Great Plains area if they were required to pay the entire cost of such a project.

Some preliminary studies north of Mangum, Oklahoma, indicate that a few rows of trees planted 40 rods apart on deep sandy soil will provide more protection to young crops during the spring months when damage from wind erosion is often severe, than a larger number of tree rows spaced farther apart.

Information gained from tree plantings in the Great Plains area about 1900 has been helpful in predicting the fate of the present shelter belt program. Earlier plantings also were made as a part of the homestead requirement in some states (Stoeckeler and Williams, 1949). Most of the black locust plantings have dwindled into brushy thickets. Catalpa plantings have not regenerated from seed. In the northern part of the Great Plains area where snow drifts into the shelter belts, the opportunity for continued growth and replacement may be somewhat better than in the southern part of the area where little snow occurs.

A tree in a dry country removes subsoil water much like alfalfa. Replacement of this moisture may be slow, and there is little evidence to indicate that tree seedlings of a majority of the species planted in the shelter belts will regenerate except under very favorable soil moisture conditions. Most of the taller trees in the shelter belt plantings such a Chinese elm, cottonwood, green ash, red cedar, and pine do not sprout from the stump after the tree is cut. Trees like black locust sprout freely when roots are severed or are damaged by rodents, or if the tree is cut before it is too old, but this species was not planted extensively. Bois de arc and mulberry are probably the most permanent trees in many of the shelter belt plantings.

Another important problem is the lack of crop protection provided on much of the land between the shelter belt strips, which are seldom less than a mile apart. Since it is unusual for the tallest trees in the average shelter belt to exceed a height of 40 or 50 ft. when mature, any benefit from reduced wind velocities will be limited to a distance of 40 or 50 rods to the leeward. Consequently, field crops planted on more than half the area between shelter belt plantings spaced one mile apart will receive no protection from reduced wind velocities. Soil movement on these areas must be controlled by other procedures such as mulch tillage, strip cropping, or deep plowing where the subsurface soil contains enough clay to develop a cloddy structure resistant to wind erosion (Harper, 1950). Mechanical methods and special cropping practices were used to control wind erosion before the shelter belts in the Great Plains area were planted. They will also be needed to protect crops on much of the land after the taller trees in the shelter belts are dead.

### 11. *Economic Problems*

Economic problems are one of the barriers which prevent some farmers from changing their method of farming to control erosion. Soil conservation farming often requires that the individual sacrifice present income or increase capital investment for future gain. This type of farming under most conditions requires diversification or a livestock system in which dairy or beef cattle must be used to consume the additional forage produced on pasture or meadow land. The greatest immediate economic benefit from a soil-conserving practice in a humid area will be obtained from the more efficient use of rainfall. However, water is not a limiting factor in crop production during many seasons. Under such conditions soil-conserving practices will increase the cost of crop production.

More labor is required to cultivate land on a contour on the average soil because of point rows or irregular shaped fields. Also no immediate benefits are obtained from financial investments required to build terraces and water disposal systems. An increase in the acreage of soil-conserving crops also will decrease farm income when the operator is not in a position to convert feed crops into beef or milk. Such factors as limited income on small farms, the cost of shifting from a cash crop to a livestock enterprise, or debt often prevent individuals who appreciate the need for erosion control from using soil-conserving procedures on their land.

During the past century farmers in the United States have produced more food than the nation could utilize. As a result world markets have determined the price of agricultural products. At the present time 28 per cent of the farms produce 70 per cent of the nation's commercial food supply. The lower cost of crop production on fertile land has created a serious enconomic problem on less productive soils, where lower yields are associated with higher production costs and especially during periods when the price of agricultural products are low.

In the northeast part of the United States what is regarded as good soil-conserving practice seems to coincide with the most profitable system of farming. Setting up a soil conservation program should be a low cost procedure in that area. In the west-central and southern part of the United States there appears to be a definite conflict between the most profitable farming practices and the known methods of soil conservation. This is the area in which the greatest loss of soil from erosion has occurred.

Owners of small farms affected by erosion are often in a difficult economic position. If much of the cultivated area is planted to grass, the farmer may be forced to purchase or rent additional land to maintain his present standard of living. Dairy farming is a logical enterprise on small farms where soil-conserving crops are grown because of the higher labor income as compared with beef production, but farmers who cannot sell whole milk will continue to be affected by serious competition from oil seed crops. Only a beginning has been made in shifting to pasture land which is too steep or too shallow for cultivated crops. The impact of such an extensive change could have an important effect on the national economy in which there is already an overproduction of butter (Crickman, 1949). However, if a farmer does not stop erosion on his cultivated acreage, eventually he will be forced off the land because of a low income from declining yields. There are enough of this kind of units in some areas to cause real concern about the future of the land and the farmers on it.

In 1944, the Census of Agriculture reported that 900,000 farm families had gross incomes of less than $400. Small farms producing one or two cash crops such as cotton, corn, or tobacco and with little or no productive livestock can utilize mechanical procedures for erosion control on sloping land, but offer the greatest resistance in making a shift to a type of farming needed to conserve the soil. Some of the conclusions reported from a study of problems in the Broad River Soil Conservation District in South Carolina by Lee and Aull (1948) are as follows: (1) Farmers with less than 50 acres of crop land make most of their income from cotton. (2) Livestock does not become a good alternative enterprise for cotton unless the necessary feed can be produced easily and cheaply and unless pasture can be provided at a reasonable cost.

Studies in the Pecan Creek watershed in east central Oklahoma by Tucker and Nelson (1940) reveal that farmers using soil-conserving practices were those who could do so without making major changes in the kind and amount of crops and livestock produced. In these studies crop yields were not increased by the methods used to control erosion.

A study of taxation in Edgefield County, South Carolina, by Peterson and Aull (1944) shows that farmers on good land paid a lower tax on their investment than farmers on poor land. The higher tax rate encouraged the farmers on the low value land to produce a higher return per acre rather than a higher return per man. Higher taxes tended to discourage livestock and forestry and favored the production of cotton, corn, and tobacco.

The problem of federal income tax has made the economics of soil management more difficult. Unless a farmer can deduct the cost of soil capital in the crops or livestock which he sells, and unless he returns as much fertility to the land as is removed by crops, erosion, and leaching, taxation will continue to consume soil capital and aid in the further depletion of the nation's resources.

Buie (1947) reports that a reduction in the acreage of cash crops had a tendency to decrease farm income. Musser (1947) suggests that crop land should be reduced 11 per cent in the north central United States and that pasture land should be increased 35 per cent. If farmers in St. Croix County, Wisconsin, changed to a grass land agriculture, there would be an increase of about 6,000 dairy cows and a decrease of 50,000 hogs. Less machinery is required to operate the grass land farms, the cost being $2,000 as compared with $2,750 on the typical hog and dairy farms (Anderson and McNall, 1945). However, a system of grass farming which protects the soil from erosion, has the disadvantage of placing all the eggs in one basket, since everything depends upon the performance of the hay crop, the dairy herd, and the dairy market. It was only a few years ago that a large number of cattle were shot under the auspices of the federal government because drought had so greatly reduced the forage supply on grassland.

Kutish (1950) reported that an Iowa farmer would need to invest about $3,000 to establish an erosion control system of farming in southeast Iowa, based on a study by Heady of 45 farms operated under a good system of erosion control, as compared with 45 similar farms on which little or no erosion control was practiced. For the first three years farms which shifted to a soil conservation program had a lower income than the non-soil conserving farms. After five years the farmers who had adopted erosion control practices had developed their livestock enterprises to a point where their income was greater than that of the cash crop farmers.

Profit from a few farms under present conditions cannot be used to predict farm income from different systems of farming over a long period of time, since an increase in the number of dairy and beef cattle resulting from the effect of a soil conservation program on feed production might cause a lower income from livestock than from cash crops on a similar unit. Fielder and Eke (1944) reported that peas and grain are grown in preference to livestock on many farms in Idaho because the cash crops yield a higher farm income and require less labor to produce, consequently there is more leisure time on the cash crop farms. Sauer (1949) collected data on the cost of establishing conservation farming plans in Illinois and found that the average farmer spent $23 per acre to improve the land and $12 per acre for additional buildings, livestock, and machinery. The farmers who invested more money in soil-improving practices raised more livestock and increased their average net income $553 per 160 acre farm over a ten-year period.

Farm surveys have been used in many areas to obtain information which would extol the advantages of a soil conservation program. This information under average conditions is not a measure of the economic benefits obtained from the use of procedures which control erosion. It normally includes the beneficial effect of soil-improving practices which must be used on all land regardless of conservation requirements. Where different farms are involved, measurements will normally show not only differences in good farming practices and managerial ability, but also under many conditions a higher income from farms which have shifted from grain production to more livestock. Collier (1945) is only one of many agricultural economists who have pointed out the fallacy of surveys which try to show the economic benefits from soil-conserving practices by comparing the income from similar farms where erosion control practices are being used and where they are not being used.

Missouri farmers are rapidly adopting a procedure which they have called ''balanced farming'' to increase farm income (Burch, 1949). It is essentially a system of good soil, crop and livestock management integrated into a family program for social and economic improvement. The program recognizes the importance of soil-conserving practices, and they are used as needed to control erosion, but they are only a part and often a small part of a balanced farming program.

About 30,000,000 acres of grassland in the Great Plains area was plowed up during World War I and an additional 2,000,000 was plowed up during World War II. Someone may ask why was the land plowed? The answer is very simple; machine farming has made it profitable to convert the organic matter and plant nutrients in the soil into wheat. Although dust storms in the early 1930's were a serious problem in the Great Plains area, the average net income of wheat farmers in eastern Colorado was $14,000 per farm in 1947 (Anderson, 1949). It would not be easy to convince a farmer that he should plant his farm to grass and raise cattle under such conditions. However, Finnell (1949) in a recent study of 259,000 acres of newly plowed land reported that 25 per cent was not suited for cultivation and 48 per cent was poor crop land. Six out of 7 acres of the land plowed prior to 1936 was flat land. A much higher percentage of the recent acreage put into cultivation is more rolling and is subject to greater potential damage from water erosion.

In Oregon lima beans and tomatos are grown on land which rents for $300 per acre because of the favorable environment for the production of this crop. Serious damage to the land can occur on sloping areas where erosion is not controlled and run-off water may remove 1 in. of top soil per year. The safe use of this land would be to plant a crop which would provide a dense vegetative cover to protect it from serious erosion. Such a procedure would greatly reduce the income from the land. Consequently, it is doubtful if a farmer would quit growing beans to prevent erosion losses until the profit from growing beans is greatly reduced, and necessity requires that some other crop be grown (Rockie and McGrew, 1932).

Winters (1937) made a study of income from southern forest land and found that loblolly pine on small farms returned a net income of 74 cents per acre with an operating cost of 16 cents per acre. It is quite evident that the physical environment of land must be very unfavorable for plant development where timber can compete economically with grass in the development of a land use program to conserve the soil.

In some areas land is purchased for its mineral value (Weitzell, 1941) or is owned primarily because of the economic return to be obtained from rent or future sale. Southern (1949) reported that Oklahoma land with only fifty to sixty years of agricultural background has had an average ownership transfer history of three to four times. In a seven-county study in Oklahoma, Arkansas, Louisiana, and Texas 34.8 per cent of the land was sold during the period 1941 to 1947. Motheral, Southern, and Crockett (1947) reported that more than half of all farm land in Nacogdoches County, Texas, was transferred to new ownership from 1941 to 1947. When land is sold, farm planning contracts with Soil Conservation Service are cancelled, consequently the sale of land may retard the progress of soil conservation if the new owner must raise cash crops to pay a mortgage. In one soil conservation district in Arkansas which had 692 agreements in 1945, 113 soil conservation contracts were cancelled because of a change in land ownership. (Northwest Arkansas Times, Fayetteville, Arkansas, May 21, 1946).

This is no sound argument against the importance of soil erosion control. However, in a country where few areas are protected by land use regulations, such as the Wisconsin Zoning Law (Wehrwein *et al.*, 1938), soil erosion will not be stopped on many farms until a change in land use must be made because of low production or some economic trend occurs which will discourage excessive soil exploitation.

The cost of a soil conservation planning program over a period of years could be rather expensive. In 1949 the federal government spent $46,584,787 for assistance in soil conservation districts. A total of 114,892 farm conservation plans were prepared during this period. If maintenance of previous farm conservation plans is not considered, the average cost of technical assistance in preparing each farm plan and running contour and terrace lines was slightly more than $400. Weitzell (1947) reported that the federal government appropriated $1,871,576,000 in behalf of soil conservation from 1937 to 1946.

### 12. *Social Problems*

Soil erosion according to Jacks (Jacks and Whyte, 1939) is a modern symptom of the maladjustment between human society and its environment. Forster (1942) is of the opinion that soil erosion alone is not the cause of the decline of communities or nations and that methods for erosion control cannot succeed unless the social and economic forces are corrected which were responsible for the development of pathological areas.

Some of the social problems which retard the progress of soil conservation in many areas are (1) few landlords require tenants to use soil-conserving practices, (2) young farmers without capital are forced to exploit the soil, (3) many individuals are not in a favorable economic position or are unwilling to reduce their acreage of row crops, or change to a livestock system of farming, and (4) a vast majority of farmers on land that is not eroding rapidly do not recognize that slow soil losses will eventually endanger the standard of living for future generations.

The most serious social problems occur on small farms, either on shallow soils, or on the fringes of regions which are most suitable for the production of a particular crop. The struggle to obtain a living on these areas under unfavorable economic conditions combined with a higher cost of production normally associated with lower yields has forced many farmers to follow a system of farming which does not preserve the physical value of the soil or replace nutrients removed when crops are harvested.

One-third of the farm operators in the United States are tenants. A large proportion of these tenants hold leases for one year and do very little to prevent erosion or to improve soil fertility. Farming to them is usually a means of obtaining wealth instead of a mode of life. Young tenants usually exploit rented land to accumulate capital so that they can become owners as soon as possible. However, the landlord should be held responsible for soil depletion whether he receives cash rent for the land or a share of the crop. Many landlords require their tenant to plant most of the cultivated land to cash crops. This has been one of the important causes of erosion on many soils. Although landlords may be interested in conserving their soils, too many of them because of convenience, or greed, continue to rent for cash, or a share of the crop, when a diversified or a livestock system of farming should be used to control erosion. This is especially true when women inherit land and know very little about farming.

In some areas where there is a possibility of discovering oil or gas, many absentee landowners have purchased land for the specific purpose of gambling on its mineral value. Most of these farms are not managed to conserve the soil. Twenty-five per cent of the absentee landowners in Oklahoma and Texas live more than 100 miles from their farms (Southern, 1949).

In 1949 a study was made of 785 farms located in 38 counties in Oklahoma in which soil conservation districts have been in operation for several years. All these farmers were enrolled in the Veterans Agricultural Training Program. Fifty-eight per cent of them were tenants. Only one-third of the tenants had a soil conservation plan, whereas, 60 per cent of the owners were cooperating with soil conservation districts. Only 22 per cent of the farmers who did not have a soil conservation plan for their farms were receiving financial aid for erosion control or soil-building practices from the Production and Marketing Administration. However, all these farmers were receiving several times as much money from the federal government as they could have earned from the PMA program.

Studies in Oklahoma show that a much lower percentage of tenants are cooperating with soil conservation districts than owner-operators. Less than one-fourth of the cooperators in the Washita River watershed, comprising all or part of seven soil conservation districts, were tenants, although more than half of the farms were operated by tenants. It is quite probable that most tenants who are using soil-conserving practices are either livestock farmers and can utilize more hay and feed crops, or conserve the soil because the landowner insists on the control of erosion to protect his investment in the land. Rented land will continue to be exploited unless landlords will assume the responsibility of telling the tenant how to farm the land to protect the soil. City people, such as bankers, merchants, doctors, and lawyers, who own farm land and do not depend upon farm income to support their families, may easily change from a system of farming which exploits the soil to a soil-conserving system. The Friends of the Land Movement has been an important factor in increasing the interest of nonresident land owners in soil conservation.

A soil conservation program is not practiced on some farms because the operators are not too dissatisfied with their present procedures. Although soil loss on deep soils may proceed as rapidly as on shallow soils, many years may be required for soil loss to greatly reduce crop production on deep soils where soil-improving methods are being used to maintain yields. Very few experimental data have been obtained to answer erosion control problems on this type of land.

Many farmers are tied down by habit and custom. It may be a lack of confidence in the results of change or lack of initiative which makes them hesitate to accept new procedures or new ideas. Miller (1939) believes that any landowner can control erosion on his farm if he wants to do it. Missouri farmers, according to Miller (1939), can be divided into three groups, depending upon their attitude toward scientific information. One group will do everything the agricultural experiment station recommends; they are "the sweet clover farmers." A second group will do part of the things recommended, but not everything. They are "the soybean farmers." A third group will not do anything the experiment station recommends. They are "the timothy hay farmers." The big job is to transfer as many farmers as possible from the third group to the second group, and then move them from the second group to the first group.

The importance of soil conservation cannot be grasped with equal rapidity by all people. The individual must appreciate the need before soil-conserving and soil-improving practices will be applied on the land. Many farmers are willing to make one improvement at a time, but hesitate to make too great a shift in their farming procedures until they are convinced that it is good economy to make the change. Where gully erosion is a problem, it has not been too difficult to obtain farmer participation in a terracing program. Where legume-cropping systems are needed to build up the nitrogen content of the soil, the more progressive farmers are the first to shift from soil exploitation to soil building. Unfortunately many soil-conserving practices do not increase crop production unless water is a limiting factor in plant development. Under such conditions farm operators must make an investment in the land which will not return immediate profit. To create a love for the soil in the minds of those who live on, or own the land, is an important job which must be accomplished before there can be a rapid expansion in the use of soil-conserving practices in any community.

## IV. SUMMARY

Progress in soil conservation has been a gradual procedure in which farmers formerly aided by educational programs and technical assistance are now supplied with financial help and technical aid for federal sources to terrace their land, contour farm, strip crop, plant legumes, etc. Money and technical knowledge will not conserve the soil. The farmer or landowner must understand the problem and be willing to do something about it. An excellent background concerning a need for erosion control was established by the county agricultural agent movement which began about 1914, but did not provide much help to farmers in many areas prior to 1920. Although many counties in the United States did not have a county agricultural agent before 1933, several million acres of land were terraced and contour farmed, and an equal or greater acreage of land was protected from erosion by soil-building rotations before several multi-million dollar federal action programs were initiated in 1933 to hasten the application of soil conservation practices on the land. Much of the credit for the progress that has been made in soil conservation during the past fifteen years should be given to these organizations. However, selling a soil conservation program to the first 50 per cent of the farmers who need to conserve their soil will be much easier than selling conservation to the last 50 per cent. Many of the farms on which erosion control practices have been recently established are operated by progressive farmers who have been working closely with other agricultural agencies for many years. Some of these farmers are livestock farmers who can conveniently use more hay and grass. Other farmers own their land and can afford to take a reduction in farm income, if necessary, to conserve the soil. On many farms very little change in present practice was required to control erosion because soil-conserving or soil-improving practices were a part of the soil management practices used on these farms.

Scientific agriculture is a relatively recent development and cannot assume much credit for the development of many soil-conserving practices, although during recent years it has perfected many details of procedure. The art of soil conservation began in many parts of the world before people could read or write. Good farmers learned to terrace their land, farm on the contour, plant crops at right angles to steep slopes, grow legumes with small grain, apply compost to conserve and improve soil fertility and use other procedures to conserve and improve their soil, centuries before soil scientists and disciples of soil conservation pointed out that soil erosion is a serious problem where torrential rains fall on sloping areas of cultivated land. Since row crops on moderate to steep slopes are the principal cause of soil erosion in humid areas, the principal job of the soil conservationist is to reduce the acreage of row crops and to establish other soil-conserving practices on such land so that soil loss will be kept below a permissible maximum.

Classification of land according to erosion susceptibility has provided a scientific approach to the erosion control problem that was not previously utilized by individuals who were engaged in the application of mechanical and vegetative procedures to retard gully and sheet erosion. Land classification is a more important problem on some farms than on others. It is especially important in the segregation of soils which are too shallow or too steep for the continued production of cultivated crops. A soil conservation survey separates cultivated land into five classes, depending upon the need for soil conservation practices. Some land needs no mechanical treatment to control erosion (see Fig. 1). As the slope increases, there is a greater need for mechanical treatment and soil-conserving cropping systems. Some soils on moderately steep slopes should not be cultivated more often than once in three to five years to prevent serious soil loss by erosion. Shallow soils on steep slopes should normally be used for pasture or forest.

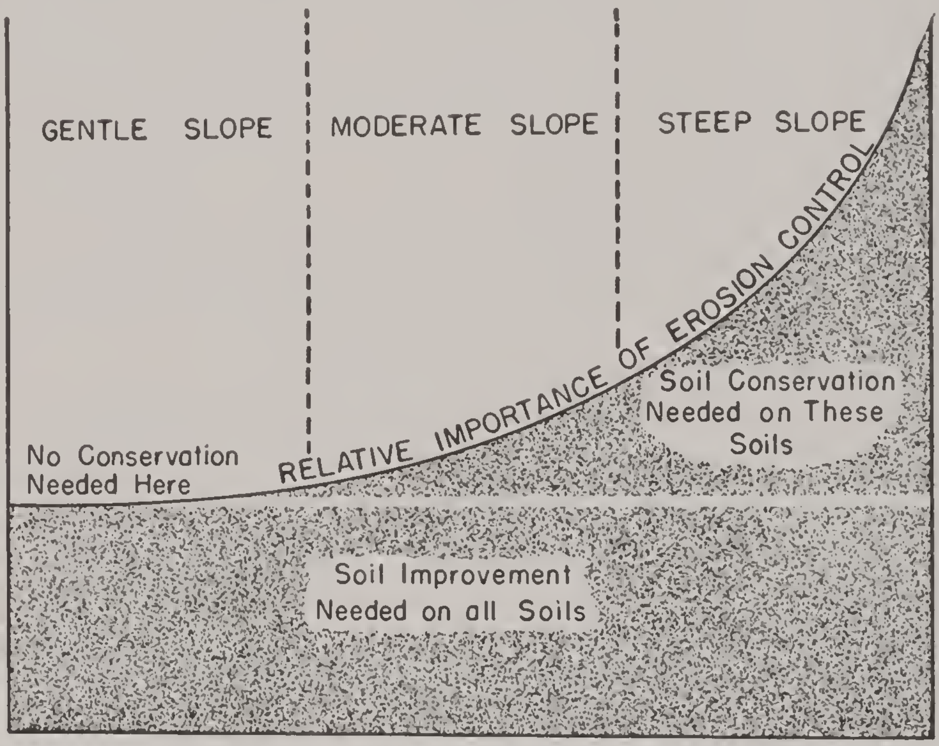
GENTLE SLOPE
MODERATE SLOPE
STEEP SLOPE
RELATIVE IMPORTANCE OF EROSION CONTROL
No Conservation Needed Here
Soil Conservation Needed on These Soils
Soil Improvement Needed on all Soils

FIG. 1. A graphic presentation of the relative need for soil improvement and soil conservation on all areas of cultivated land in a humid climate.

Research on soil conservation problems has been confined principally to a study of different mechanical and vegetative procedures that could be used to control erosion under different soil and climatic conditions. Some research has been conducted to answer questions concerning the erosion process. These problems have been investigated principally by soil physicists, soil biologists, soil chemists, and soil morphologists.

Climatologists, engineers, agronomists, and foresters also have been studying various phases of the erosion control problem.

Soil-building cropping systems which must be used to maintain or improve crop production as the natural fertility declines on account of the continued production of soil-depleting crops will also conserve the soil on sloping land. Where small grains and solid plantings of legumes or grass-legume mixtures are planted, the problem of erosion control is principally a procedure of establishing contour farming with terraces or strip cropping on the land. Row crops can be grown in a soil-building cropping system on gentle or moderate slopes, but the percentage of row crops must be decreased to conserve the soil as the slope of the land increases. This is the principal job of the soil conservationist. One row crop in three years has been recommended on moderate slopes, and one row crop in three to five years on moderately steep slopes. Row crops should not be planted on steeply sloping land. Soil erosion is greatly reduced for one or two years when a meadow or pasture sod is plowed and a row crop is planted because soil aggregates on sod land offer more resistance to the dispersing effect of raindrops than soil aggregates taken from land planted continuously to a row crop. When cover crops are planted on sloping land, the method of tillage used to prepare a seed bed for the succeeding crop has an important influence on soil loss.

Research on terracing and contour farming has shown that these procedures are the most effective methods that can be used to control run-off water on sloping cultivated land where torrential rains occur. These practices are also effective in conserving rainfall on gentle slopes in a subhumid or semi-arid region. Terraces are expensive to build and difficult to maintain on cultivated land when slopes exceed 12 or 15 per cent. Consequently, steep slopes must be protected from erosion by a solid vegetative cover or a system of crop residue management.

A comparison of the value of different grasses and legumes to protect grass waterways from the erosive effect of run-off water has been made to discover the limitations of different kinds of vegetation when subjected to varying water velocities on coarse and fine-textured soils and on different slopes. The best turf-forming grasses which are suitable for pasture in any area have been useful in the construction of grassed waterways. Mechanical structures were used in some of the earlier soil conservation programs to drop water from higher to lower elevations, but grass is used at the present time for most locations because of a lower cost. However, a vigorous grass, such as Bermuda which can easily become a serious pest when row crops are grown, may not provide the best method of water disposal when planted in a waterway across the middle of a cultivated field.

The infiltration of rain into the soil may be affected by the slope, texture and permeability of the soil, rate of rainfall, and vegetative cover. Several experiments have shown that vegetative cover has a greater beneficial effect on the rate of infiltration of water than the physical or chemical character of the soil. The resistance of soil aggregates to the dispersing effect of rain drops was greatly increased where a grass sod had been plowed for a row crop as compared with soil aggregates taken from land in continuous corn. Many studies have revealed that over-grazing of pasture land and the burning of forests will increase run-off. However, these bad management practices do not have much effect on the relative amount of soil removed from the land by sheet erosion. The lack of agreement between several investigators concerning the relation of slope to run-off has probably been due to variations in type of vegetative cover, rate of rainfall, and physical character of the different soils. A more rapid rate of absorption of water by youthful soils as compared with more mature soils may often influence the need and type of soil-conserving practices that should be used to control erosion, such as the frequency of terrace spacing or width of strip crops. The beneficial effect of soil-conserving practices as a major factor in flood control is speculative, although some measurements are being made on small watersheds. Soil-conserving practices should reduce the harmful effect of small floods where the capacity of a stream channel has not been seriously reduced by the accumulation of sediment. However, there is little evidence that such practices will have an appreciable influence on big floods. Loss of soil by erosion is not only harmful to the land, but also it may greatly reduce the efficiency of reservoirs constructed for a water supply or to produce hydroelectric power, over a period of years as a result of the gradual and sometimes rapid displacement of the water holding capacity by the sand, silt and clay carried into the reservoir by run-off water.

The management of crop residue to reduce soil loss from water and wind erosion has been studied under many different soil conditions in both semi-arid and humid climates. Tillage methods which leave a large part of the straw on the surface of the land have been used extensively in semi-arid regions. Crop yields have been very similar on subsurface tilled plots as compared with plowed plots in areas where soil moisture is usually a limiting factor in crop production. As rainfall increases, too much crop residue with a wide carbon-nitrogen ratio on or in the soil will have a harmful effect on crop production. Also a harmful effect on crop yield will be produced when large quantities of straw are left on the surface of a soil low in nitrogen content in a semi-arid region. A large quantity of crop residue on the surface of row crop land in a humid climate will slow down the rate of evaporation of moisture during periods of rainy weather and competing vegetation may be difficult to control because the surface soil will not dry sufficiently so that the land can be cultivated. Equipment used for subsurface tillage does not stir a fine-textured soil as effectively as plowing, consequently, a combination of less aeration and a less favorable environment for root development will reduce nutrient availability, thus causing a reduction in crop yield. The control of some insects, such as the corn borer, is more easily accomplished when corn land is plowed to cover the stalks. Plowing of stubble land also reduces competition from cheat and weeds which are often a problem when subsurface tillage is practiced. Since plowing sloping areas makes them more susceptible to erosion, the problem of crop residue management for erosion control is an important one. A small amount of plant residue on the surface of the ground will greatly reduce soil loss from wind or water erosion. The problem is to work out a procedure for crop residue management which will eliminate competition from undesirable vegetation, provide for the control of certain insects, leave enough cover on the land to keep soil loss below a permissible maximum and not seriously reduce crop yields. Soil-building rotations are needed along with good crop residue management wherever legumes can be grown to solve the erosion problem on sloping areas of cultivated land. Nitrogen fertilization has been helpful in maintaining wheat production in subhumid areas where large quantities of straw are left on the surface of the land by subsurface tillage to protect the land from water and wind erosion.

The relations between cropping systems, vegetative cover, and soil loss have been measured under many different soil and climatic conditions. The advantages of one cropping system over another to reduce soil losses has been discussed in many publications when both systems should have been condemned because the rate of soil loss was far greater than any reasonable estimate on the rate of soil formation. Several investigators have proposed that the average annual soil loss be reduced to less than 5 or 6 tons per acre on deep soils and under many conditions annual soil loss should not exceed 2 tons per acre. Some soil conservation experiments have been conducted without measuring soil loss, when it would appear that a knowledge of soil loss should be the most important objective of such experiments.

Experimental studies show that soil loss from pasture land is low. When the essential agronomic practices are used to establish good pasture or meadow on steep slopes, the soil conservation problem vanishes, but soil fertility will continue to be a problem as various plant nutrients become limiting factors for optimum forage production. Where there is no soil erosion problem there is no soil conservation problem. However, many soil conservationists spend much of their time on pasture improvement. One of the big jobs for the soil conservationist is to convince farmers that cultivated land on steep slopes should be converted to pasture to provide adequate protection against excessive soil losses.

Strip cropping is a soil-conserving practice that may be used on slopes too steep to terrace and on gentle slopes, but it will not control erosion on steep slopes unless soil fertility is maintained at a moderately high level. In some areas, strips of small grain between strips of corn or sorghum cannot be used because the small grain harbors insects, such as chinch bugs, which migrate to the corn and sorghums after the small grain is ripe and seriously damage these crops. Strip cropping also interferes with the optimum utilization of crop residue by livestock before all crops in a field are harvested. This method of conserving the soil is of little value in an area of torrential rainfall, unless it is used with terraces and contour farming. Strip cropping to reduce wind erosion on sandy land has been replaced quite largely by better management of crop residues, such as subsurface tillage on wheat land, and this procedure on peanut land has not been a satisfactory method for controlling wind erosion in the west-south central states.

Field shelter belt plantings in the Great Plains area initiated as one of the New Deal action programs in 1933 were established east of the region where wind erosion was most severe. These plantings in most areas have not increased crop production on adjacent land sufficiently to offset loss of income from that portion of the field occupied by the trees or tree roots. Most of the trees planted in these shelter belts will not make good posts. Previous plantings, made about 1900, indicate that the effective height of a shelter belt will decrease with time because the taller species will not be replaced naturally under a semi-arid environment.

Economic problems will continue to retard the progress of soil conservation in many localities. During the past ten years not only have economic conditions on most farms been very good, but also financial aid from federal sources has been provided to help establish soil-conserving practices on the land. Where farmers are using a soil-building cropping system and can conserve the soil by merely changing row direction, or where they are following a diversified type of farming and can conveniently use more feed crops, the cost or the inconvenience of erosion control practices will not be a serious problem. However, when a shift in cropping system is required to conserve the soil and when a change in cropping system may often cause some reduction in farm income for two or three years and possibly require the purchase of additional machinery to harvest the small grain or livestock to utilize the forage produced, many farmers will be slow to adopt the necessary soil-conserving practices to control erosion. Progress in soil conservation will be greatly retarded when soil-conserving practices have been established on all cultivated land except that acreage where row crops must be eliminated to conserve the soil and a considerable investment must be made either in farm machinery or livestock to establish a soil conservation cropping system on the land.

Soil conservation does not increase crop yield unless water is a limiting factor in crop production. It is a profitable procedure only as it permits the farmer to utilize added or natural fertility over a period of time which would otherwise be carried away by water or wind. Many economic surveys have been made to compare the incomes on farms where soil conservation practices have been used with those from other farms where no attempt has been made to conserve the soil. However, unbiased agricultural economists have pointed out that such procedures cannot show the beneficial effect of soil-conserving practices when they are not segregated from other factors which affect farm income. Such surveys normally show the benefits from soil-improving practices, or compare the income from cash crop farms with that from diversified farms on which the income from livestock makes up a considerable portion of the total income.

Social problems such as landlord-tenant relationships, will continue to retard the progress of soil conservation until landlords realize that soil-conserving practices must be used to protect their capital investment in the land. Tenants exploit the land because they have no personal interest in it. Also, many farmers do not realize that soil losses which do not appear to be excessive during any one year will eventually seriously impair the physical value of good land for the production of cultivated crops. It is often necessary for the soil conservationist to prepare a farm plan which will require a farmer to change from the production of cash crops to a livestock system of farming. When a farmer changes from cash crop production to livestock production he must learn new skills and new procedures. It is just as logical to expect a plumber or a carpenter to change his profession to that of an electrician or a bricklayer as to expect a farmer who has raised cash crops for many years to change quickly to the production of milk, mutton, or beef.

Soil conservation is an important job on sloping areas of cultivated land where soil-conserving practices are not being used to protect the land from the destructive effects of soil erosion. There are many economic forces which tend to favor soil exploitation in both humid and subhumid regions. The problem can be solved in two ways. Either landowners or operators will recognize the need and use soil-conserving practices to halt excessive soil erosion before the physical value of the land is seriously damaged, or erosion will continue as a result of bad soil management until the potential productive value of the land will be reduced to a point where it will be suitable only for pasture or forest under present economic conditions. The biggest problem in soil conservation is a human problem. Progress will be made as farmer interest increases or as necessity demands it.

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# Irrigation Agriculture and Soil Research in the United States

R. Q. PARKS

*U.S. Department of Agriculture, Beltsville, Maryland*

CONTENTS

*Page*

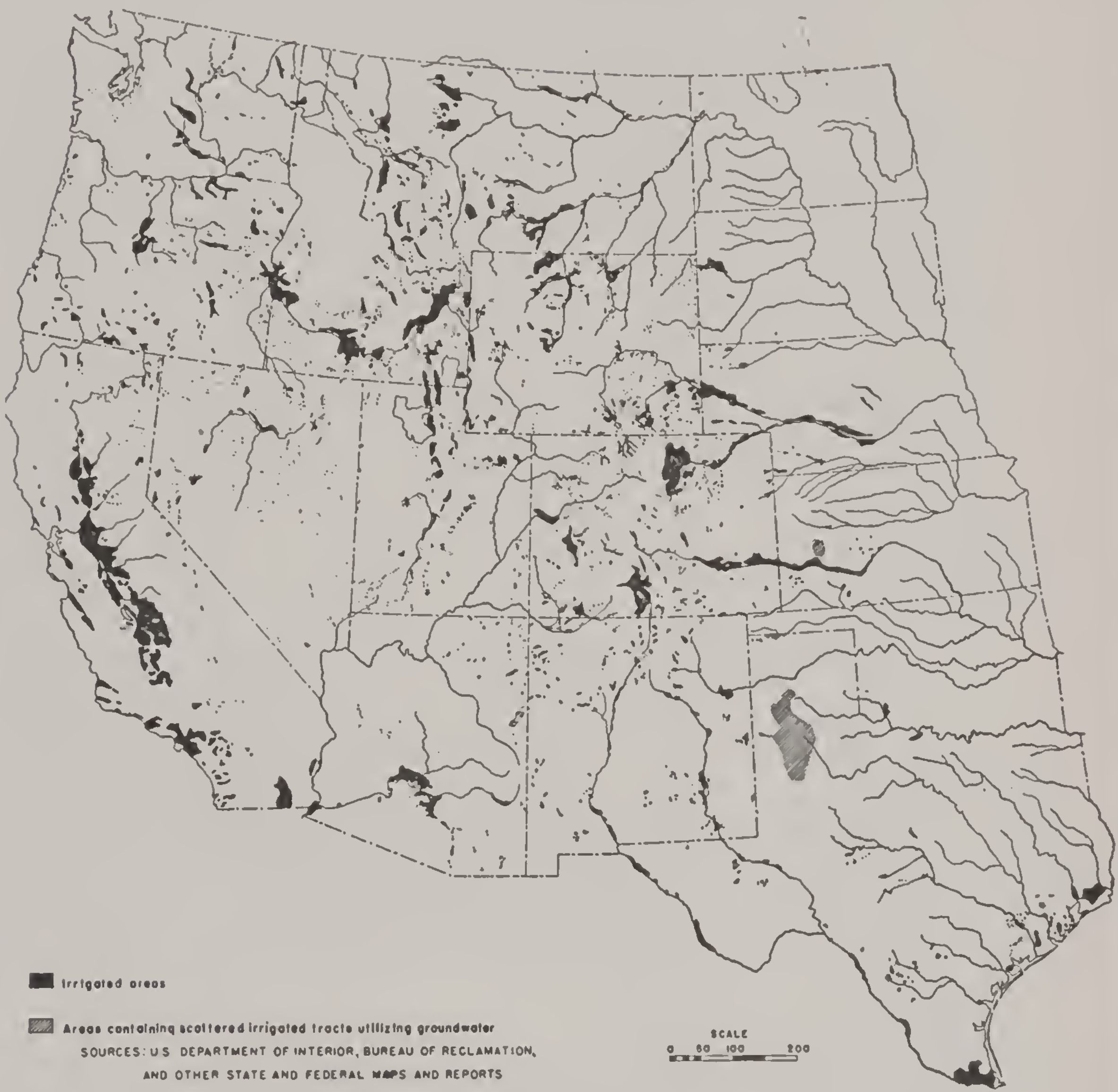
I. Introduction . . . . . . . . . . . . . . . . . . . . . . . 323
II. Historical Developments . . . . . . . . . . . . . . . . . . . 325
    1. Early American Irrigation . . . . . . . . . . . . . . . 325
    2. The Mormon Settlement and the Gold Rush . . . . . . . . . 327
III. The Modern Period . . . . . . . . . . . . . . . . . . . . 329
    1. The Bureau of Reclamation . . . . . . . . . . . . . . . 329
    2. Progress in Research . . . . . . . . . . . . . . . . . 331
    3. The Columbia River Basin . . . . . . . . . . . . . . . 334
    4. The Missouri Basin . . . . . . . . . . . . . . . . . . 338
    5. The Arkansas-White-Red River Basin . . . . . . . . . . . 339
    6. Supplemental Irrigation in Humid Areas . . . . . . . . . 340
IV. The Future . . . . . . . . . . . . . . . . . . . . . . . 342
    Acknowledgements . . . . . . . . . . . . . . . . . . . . 343
    References . . . . . . . . . . . . . . . . . . . . . . . 344

## I. Introduction

Despite an infinitely varied terrain, the West has one predominant characteristic, dryness of climate. Consequently irrigation means water for crops, but it means much more than that. Large-scale industrial and municipal developments would disappear from the West without irrigation. In 1947, irrigated crop production had a farm value of 2.4 billion dollars. Irrigation stabilizes the agriculture and most of the commerce and industry of the western states.

The irrigated area in the 17 western states is over 21 million acres, with half of the total concentrated in three states. There are 5 million acres of irrigated land in California, over 3 million acres in Colorado, and well over 2 million acres in Idaho. The remaining acreage is widely distributed among the other states. Montana and Wyoming each have approximately 1½ million acres of irrigated land, and Texas, Utah, and Oregon have just over a million acres each. Nevada, Arizona, Nebraska, New Mexico, and Washington each have over half a million acres under irrigation. North Dakota, South Dakota, Kansas, and Oklahoma at present have a combined irrigated total of less than one-quarter million acres.

The distribution of irrigated land within the various states is shown in Fig. 1. Although there are a few large projects, the pattern of distribution shows hundreds of smaller areas, usually along stream channels. Availability of water supply and suitability of soil are both reasons for this pattern. Irrigation in the West is practiced for the most part on alluvial bottom or terrace lands. These are usually permeable soils that are or can be drained. They are made up of material deposited from surrounding red and gray desert soils and mountainous areas. Geologically, these alluvial soils are young and have had little or no modification by processes of soil formation.


■ Irrigated areas
▨ Areas containing scattered irrigated tracts utilizing groundwater
SCALE
0 50 100 200

SOURCES: U.S. DEPARTMENT OF INTERIOR, BUREAU OF RECLAMATION, AND OTHER STATE AND FEDERAL MAPS AND REPORTS

Fig. 1.

Although irrigated land furnishes 30 per cent of the crop production in the 17 western states, the proportion is much higher in the far West. From 75 to 85 per cent of all crops are irrigated in California, Utah, and Wyoming, and 60 per cent of the total crop production in the

Mountain States is from irrigated land. In Nevada and Arizona practically all crops are irrigated. In the Plains States, however, only 6 per cent of the total crop production comes from irrigated land.

Irrigated crop production makes a big contribution to the total food supply of the country. Sixty per cent of the nation's sugar crops are grown under irrigation. Half of the truck and vegetable crops and 60 per cent of the fruits come from irrigated land. Food grains, hay, forage, and livestock production make up smaller but highly important contributions to the agricultural production of the country. Almost one-quarter of the population of the country is in the 17 western states, yet they furnish over one-third of our total agricultural output. The key to the present and future prosperity of the entire area is irrigation.

The art of irrigation is so old that its origins are lost in antiquity. Yet the science of irrigation agriculture is a modern development and is still advancing rapidly. One of the most important current steps is the joint use of engineering and agronomic talents in the solution of potential irrigation problems before they develop. Any new irrigation project represents a long list of unknowns—a new source of irrigation water, new crops and varieties, crop diseases and insect pests, possible soil deficiencies, and a host of other crop, soil, and water management problems. Techniques now being put into use make it possible to anticipate and solve many of these major problems in advance of settlement of the project by farmers. To understand the importance of this development, it is necessary to recall the background from which the science of irrigation agriculture is emerging.

## II. Historical Developments

### 1. *Early American Irrigation*

The art of irrigation was practiced in America by at least three different cultures, with varying degrees of engineering skill. Thousands of years ago a complex system of reservoirs and canals was constructed and used for irrigation by a prehistoric race in New Mexico. Some of these aqueducts were 10 to 80 miles in length. These works have been found covered by centuries old lava beds, and this irrigation culture was apparently completely unknown to the later inhabitants of the region.

Irrigation was later practiced in this country by the Pueblo Indian tribes, perhaps a thousand or so years ago. The cultivated acreage was not large, and was confined to the valley lands near the cliff dwellings or community buildings in Arizona, New Mexico, southwestern Colorado, and Utah. In some of these areas the traces of this earlier agriculture can still be seen. The present canals and ditches in many places follow closely the pattern laid down centuries ago. White settlers in the Salt River Valley, Arizona, actually cleaned out and used some sections of canals originally developed by a departed civilization.

This early American irrigation agriculture was primitive both in concept and practice. There were no reservoirs or large construction works, and no attempts were made to conserve flood waters for use during dry seasons. Nor are there any evidences of use of mechanical devices for lifting or pumping water, such as were developed in the Near East, the Orient, and the Mediterranean areas. This early American irrigation was entirely a gravity system. Water was diverted from a river or stream into a diversion canal near the head of a valley. By running the canal on a more gentle gradient than the river, it was possible to encompass a portion of the bench or terrace land adjoining the stream bed. Distribution of the water from the canal was then accomplished through smaller ditches or laterals and was run onto the land by furrows or by flooding.

Diversion of water from stream bed to canal was more difficult in periods of low water. It is probable that the construction of simple wattle or stone barrages was practiced to raise the stream level high enough so that water would flow off into the canal. This practice was probably confined to small streams, but even there it must have been necessary to reconstruct the diversion dams after each flood.

Locations of villages and irrigated areas were dictated by considerations of defense, water supply, and the topographic feasibility of spreading water onto the land. Even though river-bottom land is often well suited to irrigation, there must have been failures due to salinity, poor water quality, high water table, and poor soil structure. Even trial-and-error information on the irrigability of soils must have been meager and narrow in scope.

Essentially the same irrigation measures were later followed by the Mexicans of mixed Spanish and Indian origin who gradually extended their settlements from the South. Their small ditches were built as far north as Colorado, along the Rio Grande, the Gila, the Pecos, and the tributaries of the Arkansas River.

Irrigation which had been in use in Spain since Roman days was greatly expanded by the Moors in the eighth century, and rather complex irrigation systems and practices were developed. This irrigation culture was brought to the American continent by the Spanish missionaries and the explorers who came north from Mexico in the sixteenth century.

Irrigation was practiced around the early missions on the Pacific

Coast, and in the Santa Cruz Valley of southern Arizona. These developments were also primarily on the alluvial deposits making up the gently sloping valley floors along the streams. Some of these Franciscan missions developed well-integrated agricultural communities operating thousands of acres of cultivated land. Gravity irrigation was used exclusively, but some attempt was made to conserve flood waters by the construction of reservoirs. The peak of this development is indicated by the ruins of substantial dams and headworks of masonry constructed by Indian labor. Although there are some written records of this era, there is little indication that the study of soils was recognized as a science. Irrigability of land was doubtless considered to be largely a matter of engineering feasibility.

### 2. *The Mormon Settlement and the Gold Rush*

Large-scale irrigation was introduced into the West by the Mormons. It was July, 1847, when they settled at the foot of the Wasatch Mountains, in the valley of the Great Salt Lake. The land was barren, and unusual means were necessary for survival. The waters of the little canyon streams were spread upon the land, but the desert did not blossom immediately into a luxuriant garden. There were years of near failure and meager success. These English-speaking people with Northern and Central European ancestry had no traditions or experience in irrigation. Soil, crop, and water management practices were developed by trial and error. The size of farms was limited, intensive culture was practiced, and eventually much of the art of irrigation agriculture was mastered. The Mormons became a prosperous people and established extensive farming communities, based on irrigation, not only in Utah, but also in Idaho, Nevada, Wyoming, Arizona, and New Mexico.

The Mormons had barely started the development of the State of Deseret when the 1848 discovery of gold was made in California. There was a large-scale movement of people both by sea and across the plains and mountains to the West. On the western slope of the Sierras, many streams were diverted as the gold miners built ditches for placer washing. Occasionally the water from some of these ditches was put to use for irrigation. This was not a major development and was looked on primarily as an adjunct to mining. With the stoppage of hydraulic mining, the ditches built for placer washing were either abandoned or used exclusively for irrigation.

These irrigation attempts, together with the results of irrigation by the Spanish missions and the Mormon communities, attracted public attention at a time when population pressure was increasing rapidly. There were some community efforts, and large numbers of individuals brought land under irrigation. The developments were widely scattered and many were ill-conceived. Confusion was increased, since these people had but little background of common law with respect to the appropriation and use of irrigation waters.

In 1840, only a few thousand acres were irrigated by Indians, Mexicans, and the California missions. By 1860 irrigation had spread to include an estimated 20,000 acres of land. From 1860 to 1880 was an era of rapid development of small ditches or diversion canals constructed by individuals or associations of farmers. At the end of that period about 1,000,000 acres were under irrigation in the western part of the country.

During the next 20 years (1880-1900) there was a wave of speculative private irrigation developments. Huge sums of money were obtained by sale of stocks and bonds, and great irrigation works were projected. Long canals, many up to 100 miles, were planned, and some were actually built. These developments were usually of the diversion type, with little effort toward flood-water storage.

Nearly all these large-scale private and corporate developments were financial failures, but they did produce a great extension of the irrigated acreage in the West. The one million acres of irrigated land in 1880 was increased to 3½ million acres in 1890 and to nearly 8 million acres in 1900.

The failures in these earlier irrigated areas also produced a valuable body of experience. These operations made it clear that much of the land that was topographically feasible for irrigation was not agronomically suitable. There was a small but growing realization that the selection of land to be irrigated must take into account the character of the soil profile, subsoil drainage, salinity, and potential long-term productivity.

Up to this time the modern science of plant breeding was unknown, insects were not yet a serious problem, soil was any level land, and water was irrigation water regardless of its quality. The need for agricultural research and for the collection of data was not yet generally recognized.

Failures during the irrigation boom prior to 1900 focused attention on these needs, and agricultural experiment stations were established in each of the eleven western states and territories within a few years after the passage of the Hatch Act in 1887 and the establishment of the Office of Experiment Stations in the following year. During this period some agronomic investigations of irrigable areas were started, but they had little influence on the scope of developments at that time. Conditions of topography and contiguity to available water supplies remained the dominant considerations.

## III. The Modern Period

### 1. *The Bureau of Reclamation*

The period since the turn of the century has witnessed the greatest irrigation engineering development of all time, the construction of tremendous dams and storage reservoirs by the Bureau of Reclamation, often at great distances from the land to be irrigated.

The passage of the Reclamation Act by Congress in 1902 represented the fruition of years of effort by President Theodore Roosevelt and a group of associates who were keenly aware of the need for development and conservation of natural resources. The Bureau of Reclamation, established originally as the Reclamation Service in the Department of Interior, immediately began a large-scale survey of potentialities for development of land, water, and power resources. Six major projects were authorized in 1903, with a total irrigable area of over 1,000,000 acres. By the end of 1906, 24 projects were authorized, and most of them were under construction.

Unlike all previous irrigation in the West, emphasis was now placed on the storage of flood waters in large reservoirs, the first example being that formed by Roosevelt dam on the Salt River project in Arizona. Electric power was generated, often by a series of dams along the same water course.

All private irrigation development did not cease with the advent of the Bureau of Reclamation activities. As a matter of fact, the Reclamation Act actually stimulated corporate enterprises. Additional private land was brought under irrigation and several of the western states authorized corporations for the development of irrigation on public lands. This activity decreased after a few years, and it was soon generally recognized that further large-scale irrigation enterprises would usually involve federal agencies. This was the result of recognition of several factors, not the least of which was the very large cost involved. There was also growing appreciation of interrelated potentialities within the natural geographic unit, the drainage basin, which often includes parts of several states.

With the start of federal reclamation projects, land classification immediately became an important activity. The major emphasis in this work, however, was not on the delineation of irrigable areas of land. The Reclamation Act of 1902 authorized and directed the Secretary of the Interior to subdivide the irrigable public land within irrigation projects into units of such size as, in his judgment, would be adequate to support a family, with the upper limit set at 160 acres. The project boundaries having been established previously chiefly in the light of topographic conditions and available water supplies, the primary objective of the work of land classification was to delimit the farm units, and to make those on the better land smaller than those on the poorer land.

It must be remembered that the West was in the midst of its growing pains—enthusiasm was boundless and infectious—and the techniques and experience available for agronomic evaluation of arid land were far from adequate. The experiment stations were just developing their research programs and testing the applicability of agronomic practices that were successful in the humid regions. Field experiments on crop rotations and on soil and water management had hardly begun to bear fruit.

The Soil Survey had just been organized in the Department of Agriculture (1899). Its staff and budget were small, and most of the agriculture in the country was in the East. Nevertheless, surveys were started in the East and the West at the same time; one of the first surveys being in the Roswell area, in New Mexico Territory.

Soil surveyors were loaned by the Department of Agriculture to aid in making Bureau of Reclamation land classifications. Although this practice continued for many years, the Bureau of Reclamation gradually built up professional staffs and laboratory facilities of its own for land classification work.

Despite limited resources in the Federal Soil Survey, the Department of Agriculture did attempt to complete soil surveys on areas proposed for reclamation and development. One of the early surveys was on the Belle Fourche Project in South Dakota, authorized for construction in 1904. The soil survey report of 1907 expressed concern about the irrigation of certain soils on the project. Experience has shown that these apprehensions were, unfortunately, well founded.

Just as the early Mormon irrigation practices were not an overnight success, the first Bureau of Reclamation Projects were confronted with many difficulties. The basic reasons were soon recognized and many were corrected by legislative or administrative action.

The original Reclamation Act authorized that water be made available for use only on public lands. The original concept was also that the federal government would construct the storage and diversion works and conduct the water to the project boundaries. The settlers were then to distribute the water and manage the project by cooperative effort. It was found within a few years that orderly operation in a new and unstable community required that the water be actually distributed within the project. Further, the intermingling of public and private lands soon led to the irrigation of all land within the project boundaries.

The enthusiasm of the era was also reflected in the requirement that project costs be reimbursed to the federal government without interest within ten years. Over the years this requirement has been relaxed more than somewhat.

The early estimates of project costs were low and were based only on construction of the major storage and diversion works. Further, irrigation agriculture was expected to pay the entire project cost. It has since become recognized that other benefits may arise and that part of reclamation costs may appropriately be allocated to other functions, such as power, recreation, navigation, wild life, municipal and industrial uses, and flood control. Heretofore and at present, however, all costs are allocated to power and irrigation only.

It has been mentioned that the early irrigation communities were unstable, and this applied equally to private, corporate, state, and federal developments. Occasionally one still hears the disparaging statement that the savings of three successive groups of settlers were required to put an irrigation project on a sound basis. C. S. Scofield, writing in the 1912 Yearbook of the Department of Agriculture, points out that the first wave of settlers on a new irrigation project was made up of the more adventuresome, hardy, professional pioneers, intent primarily on a gamble in land speculation. It is small wonder that the Bureau of Reclamation was forced into full-scale project management. Later migrations included much larger percentages of settlers who planned to farm and make homes for their families.

Some of the difficulties on the early reclamation projects were more directly agricultural. After ten years or more of experience in the operation of these projects, it became obvious that agronomic conditions should be considered in selecting and delimiting areas of land to be irrigated, along with topography and engineering feasibility. It was further recognized that soil and crop management practices from the East could not be adopted without change in the irrigated West.

During this period a research agency was set up in the Department of Agriculture to investigate soil, water, and crop management practices on the federal reclamation projects. Experimental field stations were located in six of the projects, and the research programs developed in cooperation with the State Agricultural Experiment Stations. The Department of Agriculture Office of Western Irrigation also worked closely with the Geological Survey in investigations of salinity conditions in the West.

### 2. *Progress in Research*

Early agricultural research programs were modest in size, though they may have seemed adequate at the time. The studies did not produce immediate or radical changes in the agriculture of the West. Over the years support for agricultural research has been increased somewhat, and the combined efforts of state and federal research have resulted in improved crop varieties, better soil management, and more efficient water use. A number of fundamental advances have been made.

For years it was not appreciated that many irrigation waters contain enough dissolved salts to add a ton or more of salts to the acre during a season's irrigation. Water quality studies were built up gradually and now extend to all the major streams in the West. An understanding of the importance of water quality depended on research which showed that plants selectively remove water from the soil solution, allowing the major part of dissolved salts to accumulate in the soil.

Experience during the first years of farming on reclamation projects focused attention on situations where soluble salts did accumulate in the soils, and where applied irrigation water rapidly built up a shallow ground water table, high in soluble salts. In these situations, crops were poor, or failed completely. Obviously better methods were needed for characterizing the irrigability of land. This need was met in part by programs of exploratory examinations of soil and subsoil conditions in lands already irrigated, as well as in lands available for development.

A great deal of research has since been focused on the many phases of this broad problem of soil permeability and drainage. Methods have been developed for characterizing the permeability of soil profiles and of the underlying strata. Intensive studies have been made of problem areas. Chemical, physical, biological, and engineering techniques have been used in characterizing and improving soil permeability, and in working out methods and systems for drainage. Despite these major accomplishments, drainage investigations still do not receive adequate emphasis in planning most irrigation developments. Over one million acres of irrigated land in the eleven western states were abandoned during the decade 1930–40, largely because of salinity, drainage, and permeability problems. Much of this land could be reclaimed again, and other millions of acres improved, but it would take an agricultural research program of much greater magnitude than the present one.

Other broad fields of research that have contributed greatly to the understanding and management of irrigated soils are the crystalline nature of clays, the different types of clay minerals, and the physical effects of different cations held on the exchange complex. As a matter of fact, both irrigation and fertility practices are being steadily improved by continuing research on the chemistry of the saline, alkali, and calcareous soils of the West, and the physiology of crop response to varying alkali and salinity conditions.

The water requirements of various crop plants have been investigated under a wide range of soil, water, and climatic conditions. Methods of characterizing the availability of soil water to plants represent a major advance. The ease with which a plant extracts water from a soil varies with soil texture, with moisture content in a given soil, and with content of soluble salts. Before this was appreciated, the tendency was to use limited quantities of a saline irrigation water. Research has shown conclusively that moisture stress due to osmotic effects of dissolved salts requires use of extra irrigation water, and that additional applications are also required in leaching accumulations of soluble salts out of the root zone.

These soil and water studies led to the concept of salt balance, or the relationship between total input of salts for an irrigation project and total output in the drainage waters. This type of balance sheet is watched closely from year to year on a number of projects as an overall guide to the efficiency of irrigation, drainage, and water management.

Methods of applying water, control of erosion on irrigated land, reducing leaching losses from canals, and prevention of silting up of reservoirs have all been the subject of important research, with resultant improvement of land and water management practices.

Another major fallacy has been that all desert soils are inherently fertile. Research has shown that many of them are rich in potash, but that there is a wide range in levels of available phosphate. Yet the soils of the West as a whole are the most nitrogen-deficient soils of the country.

The research accomplishments of the State Agricultural Experiment Stations and the U.S. Department of Agriculture during the last few decades have been varied and important. During this same period, state extension and federal operation agencies endeavored to promote the wide-scale acceptance of these research advances. Their success was variable, and in some cases it left much to be desired. In many cases, the research results available were not adequate.

Experience with new settlers indicated the need for more and more complete development of irrigation projects, lands, and farms before release to settlers. The initial experiment in bringing water to the project boundaries was soon modified to include construction of the complete canal distribution system. Further approaches have since been made to the problem of predevelopment: (1) preparing the land for irrigation by leveling operations, (2) construction of farm ditches, and (3) most recently, establishing a crop on the land before opening it for entry and occupation. Still another step has been the establishment in recent years of demonstration farms to illustrate to new settlers the best available soil, water, and crop management practices. Lack of success in some instances has been unavoidable, since the program was designed to demonstrate the answers to problems that had not yet been solved.

### 3. *The Columbia River Basin*

A workable and notably successful solution to this need has been found in the combination research and demonstration farms, such as are now being established in the Columbia River Basin and elsewhere on Bureau of Reclamation developments.

The Columbia Basin Project was authorized in 1935, designed to irrigate approximately 1,000,000 acres of land in south-central Washington. Construction of the Grand Coulee Dam and the main carriage system is nearly completed. Construction of the distribution system is well under way, and water from the permanent system should be available to the first farm units in 1952, with additional acreages brought under irrigation over a period of several years. Small areas irrigated by temporary pumping plants are already in production.

The wide scope and great detail of planning are reflected in the series of published reports of Columbia Basin Joint Investigations, conducted by appropriate state and federal agencies, over the period 1939—1945. During the planning and early construction stages a new type of development farm program was conceived and put into operation. The planning and execution of this program have involved the joint efforts of the Bureau of Reclamation, the Washington State Agricultural Experiment Station, and the Agricultural Research Administration of the U.S. Department of Agriculture.

Scientific research staffs and laboratory facilities were made available in 1945, soils were surveyed, and representative farm sites were selected. Water for these farms was pumped from deep wells, or directly from the river. Research was thus begun on modern irrigation farms, two to five years in advance of delivery of water to the surrounding desert lands.

These development farms are well integrated farm units, 40 to 160 acres in size. Most of the area is devoted to field scale demonstration of the best available soil, water, and crop management practices. Ten to 25 per cent of the area is devoted to intensive agricultural research. The development farms are on government land, developed by the Bureau of Reclamation and leased to a farm operator, who is given an option on eventual purchase of the farm.

Field experiments in fertilization, irrigation, and crop management are rotated within the entire farm operation to make maximum use of crop sequence effects in these studies. Experimental results are reviewed in a general conference with all state and federal agencies each fall, and on the basis of each year's results, a mutually agreeable plan is developed for the operation of the research and demonstration phases of the farm program for the following year.

While these development farms were being organized, new lines of research were started on the State Irrigation Field Stations at Prosser, Washington, and Hermiston, Oregon, both within the Columbia Basin. Research is now in progress on development farms in the Columbia Basin Project itself, at Moses Lake, Pasco, and Winchester; and work on the fourth development farm at Burke, Washington, will begin during the 1951 season.

The results of research in the Columbia Basin during these last few years have exceeded the most optimistic expectations, and the reasons are several. First, the Columbia Basin is favored both as to climate and soils and is well adapted to a highly productive agriculture. Second, investigations of crops for the project were based on a number of years of previous research in irrigation agriculture at the Prosser, Washington, and Hermiston, Oregon, Irrigation Experiment Stations. Last, but probably not least, credit must be given to all the advantages inherent in the development-research farm system.

The traditional experimental method has involved holding constant all variables but one and measuring the effects of changes in that single variable. Crop production, however, is the synthesis of a host of soil, water, genetic, and climatic variables. Their interplay produces a myriad of cross and supplementary effects. A growing appreciation of the importance of these interrelationships among crop production factors, together with advances in the field of biometrics, has made it possible to design and interpret multifactor field experiments of a complexity never attempted heretofore. Instead of studying rates of nitrogen fertilization of a crop, with all other factors held constant, several nitrogen rates are applied to each of several plant populations. Such experiments have also involved variables in irrigation rates, crop strains or varieties, crop sequence, tillage methods, major and minor element fertilization, and fertilizer placement.

The results of corn production studies at Hermiston, Oregon, illustrate the type of relationships being found with this experimental approach. When current practices were modified to use additional irrigation water on Ephrata loamy sand, with nitrogen fertilization at 60 lb. per acre, there was little or no increase in corn yields (Fig. 2). As the fertilizer applications were raised, two important relationships were found. First, limited supplies of irrigation water were used more efficiently, as corn yields were increased from 50 to over 90 bushels per acre. Second, and more striking, the increased supply of irrigation water was used with even greater efficiency, as nitrogen applications were increased. The top yield in this experiment was over 130 bushels of corn per acre. Similar results with corn have been obtained on the Moses Lake development farm, and the same type of relationship is being found in other studies in the Columbia Basin, as well as in other areas.

An essential corollary of this type of combined approach is the greater intensity of experimentation required. Instead of comparing 3, 5, or 7 irrigations per season, an understanding of soil moisture relationships requires daily measurement of actual soil moisture tensions at varying depths in the soil profile to regulate a truly functional irrigation rate variable. Plant composition and rate of nutrient uptake are determined for the various fertilization and cultural treatments. It has been common in the past for one investigator to put out half a dozen

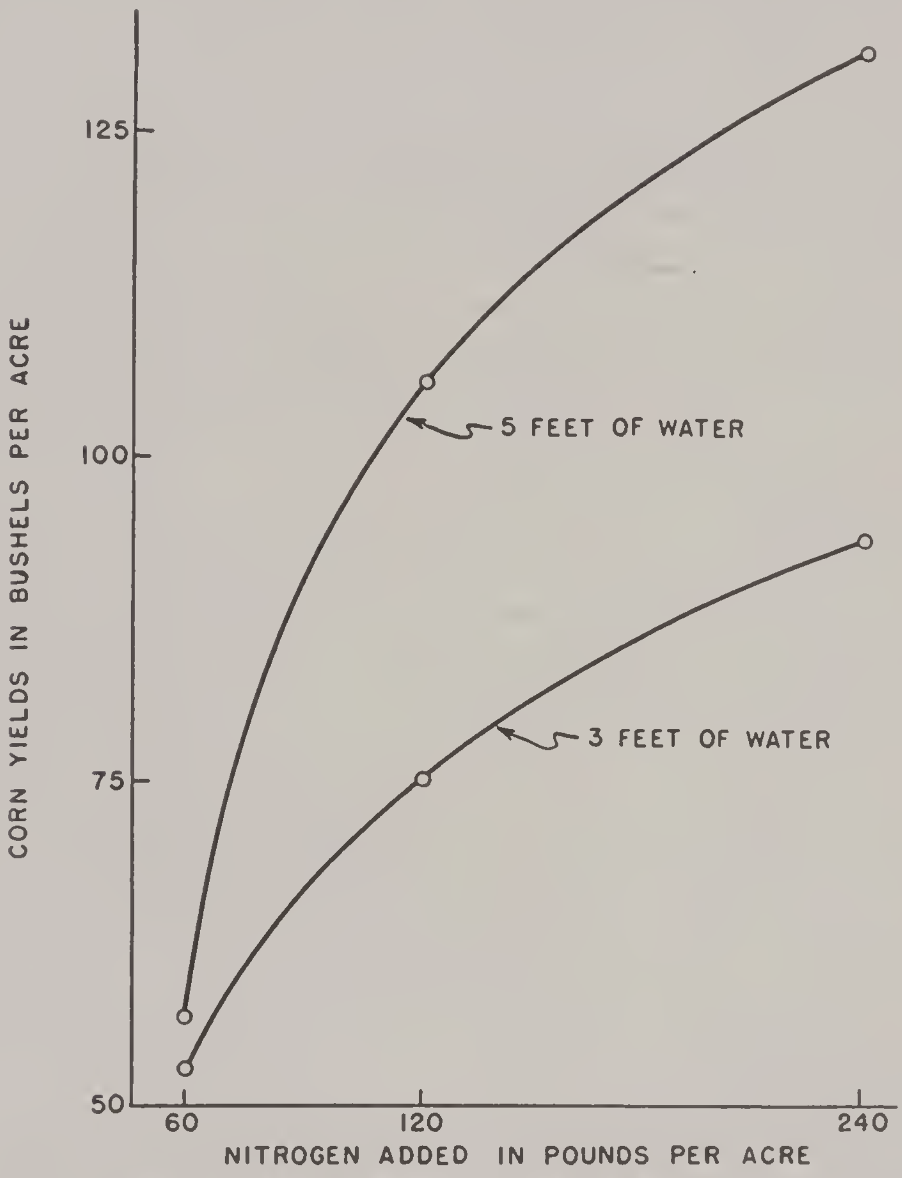


FIG. 2. The effect of varying rates of irrigation and nitrogen fertilization on corn yields at Hermiston, Oregon.

or a dozen field experiments with facilities to do little more than determine yields at the end of the season. On each of the Columbia Basin development farms one full-time technician gives daily attention to soil, water, and crop measurements and sampling on the research plots. Each field experiment is the joint effort of several of the professional staff, and often half a dozen men are at work on field or laboratory measurements of a single experiment. This method of soil management research does not decrease the need for basic laboratory research; it actually depends on an acceleration of fundamental studies. But there is also a clear need for a more intensive and more basic type of attack on practical problems as they exist under field conditions.

When the new settlers take over their land in the Columbia Basin Project in 1952, and the following years, they will be able to turn immediately to cash crops, alfalfa for hay, sugar beets, corn, small grains, and vegetables. Further, they will have sound, concise recommendations as to the best-known crop varieties, fertilizer needs, and irrigation practices.

The experimental program has shown that optimum combinations of irrigation rates, crop varieties, and fertilizer practices are the key to exceptionally high yields, as high as 37 tons per acre of sugar beets, nearly 9 tons of alfalfa hay, and up to 170 bushels of corn. Sorghum, with yields of 155 bushels per acre, holds excellent possibilities as a small grain for this region, but it will have to compete with other small grains, which also have given high yields under good management.

The research programs on the Columbia Basin development farms have been concerned with the immediate problems of fertility and water requirements, cover crop needs and benefits, soil deficiencies, adapted crop varieties and hybrids, and some of the diseases of these crops, yet many more problems remain. Salinity and drainage problems are expected and must be studied on the soils of the Burke area. Crop rotation and soil improvement studies are needed. Crop diseases may be expected to increase and means must be devised for their control. Pastures, seed production, and other alternative farm enterprises must be explored and developed. Studies on consumptive use of water are needed, and economic analyses of the experimental data will be required in formulating farmer recommendations. Much has been accomplished, but still more remains to be done. Yet it is clear already that the new settler on this project will begin farming with a better understanding of his soil, water, and crop management problems, and of methods for their solution or control, than has ever before been the case in the history of American irrigation agriculture.

### 4. *The Missouri Basin*

The Missouri River Basin Project was authorized by the Congress in 1944 and is now under construction by the Bureau of Reclamation and the U.S. Army Corps of Engineers. Over half a million square miles are included in this basin, formed by all or part of seven North Central, Plains, and Mountain States. The ultimate irrigable area has been estimated at over five million acres, but this figure may prove to be high.

The introduction of irrigation into the central and eastern parts of the Missouri Valley introduces problems which generally have not been encountered in previous irrigation projects in the United States. Particularly in the Dakotas, much of the land is rolling, and the soil is thin, making leveling of these areas impractical. New methods of water application must be devised, or existing methods modified, to meet these conditions. A large part of the area is made up of glacial soils where irregular or ''kettle hole'' topography will make difficult both distribution of water and surface drainage. Many of these soils and substrata have poor permeability, and some have accumulations of salts within the soil profile.

Under these conditions agricultural feasibility and engineering feasibility of irrigation may well differ somewhat. The problem is being met realistically by a speed-up of soil survey activities by the U.S. Department of Agriculture and the State Agricultural Experiment Stations. These surveys are following the order of priority dictated by the construction program. If their completion can be accelerated, the soil surveys will be useful to the Bureau of Reclamation in connection with its land classification activities and in final decisions as to irrigability of lands.

The development farm system is also playing a key role in the irrigation research activities in the Missouri Basin. Research on fertilization, irrigation methods, and crop varieties has been under way for two seasons on development farms at Bowbells and Mandan, North Dakota, and at Redfield and Huron, South Dakota. Considerable emphasis is being placed on experiments on pasture and forage crop management. The adaptation of legume and grass varieties is being determined under different irrigation practices. Fertilization needs of both sod and row crops are being determined, and soil permeability, drainage, salinity, and irrigation rate and method studies are being planned. The problems are proving to be fully as difficult as was anticipated, and the current agricultural research effort is not of the magnitude required to cope with this vast development program. A many-fold increase in support of agricultural research will no doubt result from the Missouri River Basin Agricultural Program, presented to the Congress late in 1949.

As it developed in the West, the project system of irrigation involves furnishing water to all irrigable land within the project boundaries. This concept appears to have been carried eastward into the Missouri Basin without serious consideration of alternative irrigation development procedures.

In the arid West, crops depend almost entirely on irrigation for their water supply. Planting and irrigation schedules are staggered so that a modest head of water can be rotated from one field to the next, in order of need. The situation in the subhumid parts of the Missouri Basin is quite different. Rainfall will furnish a sizable part of the crop water requirement, even on irrigated land. A good rain will wet up the soil in the root zone on all fields in an area at one time. When the crops begin to need water, all the fields in the entire area will need irrigation at the same time. Irrigation water must be available on demand, if serious drought injury is to be avoided, and the schedule of such demands will be sporadic, depending upon a most unpredictable rainfall distribution. The engineering design features of western irrigation projects would hardly meet these requirements.

An established agriculture exists in the Missouri Basin, currently a fairly prosperous one. The growing season is short, and the irrigation season will be even shorter, only one or two irrigations may be needed for a crop. Under such conditions, irrigation in much of the Missouri Basin takes on many of the aspects of supplemental irrigation. A high percentage of the farms could integrate a limited acreage of fruit, vegetables, or supplemental forage crops into existing farming operations. Water distribution problems will be baffling under any such system, but the manifold advantages to the farmers and to the agriculture of the area suggest that serious consideration should be given to the development of one or more alternatives dealing with the irrigation of noncontiguous areas of land.

### 5. *The Arkansas-White-Red River Basin*

This is the newest drainage basin program. Some segments are already authorized, a little construction is under way, but most of the program is still in the planning stages. It is encouraging to note that representatives of state and federal agricultural agencies are already working actively with Bureau of Reclamation and U.S. Army Corps of Engineers planning groups. During the next two years generalized soil survey maps of the entire basin will be prepared from existing soil association maps. It is hoped that intensive surveys can be made of projects in advanced planning stages. Special drainage and salinity investigations are planned for suspected problem areas. Development farm sites will be selected, and an agricultural research program will be planned and put into action years in advance of irrigation development of the area itself. Here more than ever before, agricultural science will aid in planning the agricultural phases of a reclamation development.

### 6. *Supplemental Irrigation in Humid Areas*

The 31 eastern states comprise, roughly, the humid region of this country. Although the climate is classed as humid, droughts during the growing season are common. In this area, supplemental irrigation is used primarily to make up for poor distribution of rainfall during the growing season.

Except for alluvial lands, soil and topography are such that surface ditches and furrow irrigation are usually not feasible. Sprinkler irrigation systems are used almost exclusively. Rotational use of water from field to field is feasible to a far less degree than in the West. When it is time to irrigate one field, it is time to irrigate the entire acreage. Consequently the term ''supplemental'' is apt both as to use of additional water and also in describing the way irrigation on relatively small acreages is coming into use as just one part of more intensive farm management systems. Fruit, vegetable, and specialty crops make up the largest part of the acreage, but with continually greater interest in supplemental irrigation of pastures and general farm crops.

Supplemental irrigation in the humid regions has had an interesting though sporadic history. For fifty years there have been a few hundred acres irrigated in nearly every one of the eastern states, and in some periods the figure has grown to a few thousand acres. As a matter of fact, this interest has gone through several cycles of resurgence. The current development, however, has been far more rapid and extensive than previous expansions.

Irrigated acreages in the East were not even reported in the agricultural census prior to 1939 and probably totaled a few thousand acres during the preceding decade. By 1944 the area receiving supplemental irrigation had grown to 270,000 acres, and the total amount of land now being irrigated in the East probably exceeds 500,000 acres, in addition to another million acres of irrigated rice.

Supplemental irrigation has developed, for the most part, without the blessing or guidance of agronomic research. There are exceptions, but farmer interest and engineering experiments and experience have been the major factors. Agricultural engineers of state and federal research agencies and of the irrigation equipment companies have been active in this field for a number of years. In very recent years agronomic experiments have been designed to study the most efficient fertilization and crop management practices under supplemental irrigation. This research program is modest, and in many cases it is not of the intensity required for rapid progress in this field.

Although irrigation in the East has been an individual matter so far, some large group projects are being considered. The first phase of the central and southern Florida comprehensive project has been authorized by Congress. This work by the Corps of Engineers will provide drainage and supply water for subirrigation of over 2,000,000 acres if completed as now planned. In addition, a few local soil conservation districts have considered joint development of supplemental irrigation facilities.

Two factors will tend to keep Eastern irrigation developments on a relatively small individual basis for a number of years. First, a tremendous expansion in irrigation acreage can be brought about without large-scale construction or comprehensive projects. And since irrigation in the East is used to supplement a usually adequate rainfall, it involves relatively small amounts of additional water at a critical time. It seems improbable that Eastern irrigation will ever need the huge storage capacities that are required in the West.

The role irrigation will play in the East is not clear. As a matter of fact, irrigation development in the East today is as tentative, confused, and disorganized as was true in the West one hundred years ago. Quite aside from the question of economics, there is no clear picture of the physical potentials—land and water—nor of the legal complications that will be involved.

Agriculturists have estimated the potentially irrigable acreage in the humid region at from 2 to 50 million acres of land. The precision of these estimates leaves something to be desired, and there is some basis for the belief that the actual value is not even within this range. A study of available soil survey information on the soils of Georgia indicates that from the standpoints of topography and soil permeability, from 8 to 12 million acres of land might be considered as potentially irrigable. This is in addition to large acreages of flat coastal land that might be improved by drainage.

The water supply picture is an even bigger question mark. There are over one hundred all-season streams that reach the Atlantic or Gulf coasts, and probably nearly as many that flow north and west. Not all this stream flow can be considered as available for irrigation, as large demands are made for municipal, industrial, navigation, wildlife, and pollution abatement needs. Most river basin commissions and study groups in the East have so far given little consideration to potential needs and use of stream flow for supplemental irrigation. As a matter of fact such use has a most tenuous legal standing. An irrigator in the East does not establish a water right by making such use and may be enjoined from continuing this practice. There is no body of water law in most of the eastern states, and the few court decisions have been made on the basis of the English common law doctrine of riparian rights, rather than the concept of prior beneficial use, which has evolved in the western states. Michigan and Pennsylvania are working on proposed water rights legislation, and the other eastern states are or soon will be vitally concerned with this problem.

The ground-water supply picture is even less optimistic, with many chemical and processing industries switching from ground to surface water supplies, because of a falling water table and depleted reserves.

Still another source of water supply for supplemental irrigation is the vast network of farm ponds or small lakes being created throughout the East. Rough estimates would indicate that such ponds, filled from watersheds only a few acres in size, might be adequate to supply water for supplemental irrigation of nearly all the suitable land. No determination has been made of the effect which such widespread conservation of diffuse surface waters would have on ground water levels and stream flow.

## IV. The Future

The Bureau of Reclamation has estimated that there are 21.5 million acres of irrigated land in the West, and that this can ultimately be increased to approximately 38 million acres. The reclamation program schedules the development of 1.6 million acres of this land during the period 1950-1956, together with more adequate supplies of water for existing acreages of irrigated land. The remaining potential of 15 million acres of land in the West is to receive continuing study as the program of work for years in the future.

Plans for an expanded soil research program to meet the needs of this new irrigated land are less definite. The trend is in the direction of more comprehensive soil survey and agronomic information for use in the delineation of areas of irrigable land. The development-farm system of soil management research and demonstration also should be continued and improved.

Instead of decreasing, the need for such research is actually becoming greater. Most of the good land in the West is already under irrigation. As water supplies are made available to poorer land and problem soils, the need for irrigation research becomes more urgent. Vast sums of public money will be required in the development of future irrigation projects. Without adequate research, huge mistakes are almost unavoidable. The current thin thread of modest but aggressive agricultural research programs does not constitute adequate guidance for these developments. Ways must be developed to make a more convincing presentation of agricultural research needs.

Enough experimental work has been done to prove that supplemental irrigation will produce large increases in yields of crops and pastures in the humid region. The economic question of whether the increased output will raise farm income enough to justify the higher cost is yet to be decided. The cost of an irrigation system in the humid region is rather high and might be burdensome in years when prices are low.

On an increasing number of farms, however, the benefits appear to outweigh the disadvantages. Irrigation in the East will probably continue to increase, and it might increase greatly. To keep this development on a sound basis, there is pressing need for intensified research—a program that would work out optimum combinations of varieties, disease control, fertilization, and cultural practices, with various irrigation rates and methods.

The federal government agencies and the various states have not as yet seen fit to begin the development of broad, long-term plans, dealing with the physical potentialities for supplemental irrigation, drainage, and land reclamation in the humid region. Such studies would be of inestimable value over the next few decades, in resource development and industrial expansion, and in the efficient planning of pertinent agricultural research.

## ACKNOWLEDGEMENTS

The scope of this paper precludes a comprehensive bibliography of soil research related to irrigation agriculture. Major research developments have been referred to broadly in terms of whole subject matter fields, even though in many cases dozens of technical papers have contributed to a given advance.

A major purpose of the present paper is to indicate the place of soil research in past and present irrigation developments. This is essentially an interpretive analysis for which the author takes full responsibility. Varied sources have contributed to the background of this paper. Some of the general information and concepts come from contact with farmers, water users association officials, and teachers in Arizona. In more recent years the author has had the benefit of contacts with a large number of state and federal officials concerned with irrigation agriculture. Acknowledgement for assistance is due all of them, but special mention must be made of the help of C. S. Scofield, formerly Head of the Division of Western Irrigation, now retired, but an interested and active collaborator with the Division of Soil Management and Irrigation, Bureau of Plant Industry, Soils, and Agricultural Engineering.

In addition to the above general sources of information and ideas, the following references furnished much of the history and all the statistics concerning the development of irrigation agriculture in the West.

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# Author Index

Names in parentheses indicate co-authors and are included to assist in locating references where a particular name is not on a given page.

*Example:* Aicher, J. C., 278 (see Pope), *322*, means that Pope *et al.* will be mentioned on page 278, the *et al.* accounting for Aicher. This article can be located under Pope in the list of references.

Numbers in italics refer to the pages on which references are listed in bibliographies at the end of each article.

A

Aandahl, A. R., 34, 52, 59, 65, 66, *86*
Aasheim, T. S., 291, *319*
Abel, F. A. E., 124, *159*
Adams, J. R., 13, *87*
Ahlgren, Gilbert H., 107, *110*
Ahlgren, H. L., 223, 234, 235, *240*, *241*, 297, *319*
Aicher, J. C., 278 (see Pope), *322*
Akamine, E. K., 224 (see also Wilsie), *241*
Akerberg, E., 223, *240*
Akers, T. F., 101, 108, *110*
Albieter, J. K., 47, 75, *87*
Albert, W. B., 97 (see Graber), 98 (see Graber), 101 (see Graber), *110*
Albrecht, W. A., 48, *88*, 114, 135, *159*
Alderfer, R. B., 287, *319*
Aleksandrov, V. G., 154, *159*
Alexander, L. T., 12, 17, 19, 24, 29, 43, *86*, *87*, *89*, 114, 138, *159*, *161*
Allaway, W. H., 14, 22, 23, 24, 25, 26, 27, 34, 73, *88*, *90*, 128, 150, *159*, *162*
Allison, F. E., 153, *159*
Allison, R. V., 69, *86*, 248, *263*
Alway, F. J., 71, 72, 84, *86*
Anderson, A. C., 32, *86*
Anderson, Arthur, 94, 95, 101, 103, 107, 108, *111*
Anderson, F. A., 307, *319*
Anderson, H. O., 306, *319*
Anderson, M. S., 8, 51, *87*, 115, *159*
Anderson, P. J., 259, *263*
Andrews, J. S., 284, *321*
Andrews, John S., 202, 221, *240*
Andrews, W. B., 157, *159*
Armstrong, J. M., 94, *110*
Arny, A. C., 99, *110*
Attoe, O. J., 118, 124, 125, 126, 128, 129, 137, 142, 149, 150, *159*, 161, *164*
Atwood, S. S., 234, *240*
Aubert, G., 39, 40, 41, 42, *86*
Augustine, M. T., 277 (see Copley), *320*
Aull, G. H., 305, *321*, *322*
Aumer, J. P., 123, *161*
Avdulov, N. P., 211, 220, *240*
Ayres, A. S., 18, 20, 21, *86*, 118, 124, 125, 127, 129, 142, 145, 146, 149, 151, 157 158, *160*
Ayyanger, G. N. Rangaswami, 231, *240*

B

Bachtell, Myron A., 102, 107, *110*
Bailey, R. W., 288, *319*
Bailey, T. A., 138, 142, *160*, *161*
Baker, K. G., 221, *240*
Baldwin, M., 15, 39, 40, 41, 64, *86*
Ball, C. R., 229, 230, *240*
Barnes, T. W., 144, *163*
Barnett, A. P., 295, *319*
Barshad, I., 121, 122, 133, 140, 141, 142, 152, *160*
Bartholomew, R. P., 118, 126, 135, *160*, 279, *319*
Bassalik, K., 153, *160*
Basu, J. K., 22, *86*
Batchelor, H. W., 154, *162*
Bauer, F. C., 68, 71, 72, *86*
Baver, L. D., 139, 152, *163*, 290, *319*
Beale, O. W., 287 (see Peele), *321*
Bear, F. E., 124, 125, 147, 149, *160*, *162*
Becraft, R. J., 288, *319*
Beddows, A. R., 237, *240*
Bell, F. G., 278 (see Pope), 279, 280 (see Copley), 282 (see Smith), 283, 287 (see Borst), 288 (see Copley),

294 (see Smith), 297 (see Borst), 301 (see Smith, Hill, Hays), *319*, *320*, *321*, *322*
Benedict, M. R., 272, *319*
Bennett, H. H., 69, 86, 266, 267, 273, 274, 276, 300, *319*
Bennett, H. W., 218, 222, *240*
Bergquist, H. R., 19, 20, *88*
Bertramson, B. R., 124, 127, 129, 134, *160*, *163*
Bessey, E. A., 246, *263*
Bizzel, J. A., 144, *162*
Blair, A. W., 122, *162*
Blanck, E., 120, *160*
Blaser, R. E., 213, 225, 229, *240*
Bledsoe, R. P., 210, *240*
Blume, J. M., 137, *160*
Blumenstock, D. I., 289, *319*
Bodman, G. B., 43, *86*, 157, *161*
Borland, J. W., 124, *160*
Bonnet, J. A., 17, 18, 20, *86*
Borst, H. L., 283, 287, 289, 297, *319*
Bower, C. A., 151, 152, 153, 156, *160*
Boynton, D., 149, *160*
Bradfield, R., 62, 64, 73, 75, 81, 84, 85, *86*, 146, *163*
Bradley, W. F., 132, 133, 134, *161*
Bray, R. H., 34, *86*, 116, 118, 125, 126, 127, 131, 132, 133, 134, 135, 136, 141, 142, 145, *160*, *161*
Breazeale, J. F., 39, 44, 45, *86*, 144, *160*
Breland, H. L., 124, *160*
Bridge, J., 42, 70, *86*
Briggs, L. J., 144, *160*
Britt, C. S., 283, *320*
Brittingham, W. H., 223, *240*
Brown, A. L., 34, *86*
Brown, B. A., 94, 98, 101, 104, 105, *110*
Brown, G. F., 300, *321*
Brown, I. C., 10, 12, 13, 20, 23, 28, 29, 30, 33, 35, *86*, *87*, 118, 126, 131, 135, 142, 149, *163*
Brown, J. G., 149, *162*
Browning, D. R., 37, 38, 58, *90*, *91*
Browning, G. M., 54, 56, 58, 60, 63, 64, 74, 78, 81, *87*, *91*, 156, *160*, 279, 282, 284, 293, 295, *319*
Broyer, T. C., 155, *161*
Buehrer, T. F., 140, *160*
Buie, T. S., 298, 306, *319*
Burcalow, F. V., 105, *110*
Burch, J. W., 307, *319*
Burlison, W. L., 101, 103, 108, *110*
Burrage, C. H., 63, *87*
Burrell, A. B., 149, *160*
Burton, Glenn W., 200, 202, 203, 204, 205, 206, 207, 208, 209, 211, 212, 214, 215, 217, 218, 219, 221, 225, 226, 229, 230, 231, 235, 238, *240*
Byers, H. G., 10, 12, 13, 17, 19, 20, 23, 28, 29, 30, 33, 35, *86*, *87*

C

Cady, J. G., 34, 37, 38, 39, 57, *87*, *89*
Caillere, S., 121, 134, 140, *160*
Caldwell, A. C., 25, 34, *86*, *87*
Campanile, S., 127, *160*
Carbery, M., 32, *89*
Carlton, E. A., 75, *87*, 293 (see Free), 301 (see Free), *320*
Carnahan, H. L., 230 (see Fortman), *240*
Carolus, R. L., 147, *160*
Carr, R. B., 101, *110*
Carreker, J. R., 295, *319*
Carson, C. M., 254, *263*
Carter, D. G., 279, *319*
Carter, John, Jr., 100 (see Staten), 101 (see Staten), 108 (see Staten), *111*
Carter, W., 247, *263*
Chamblee, D. S., 236, *240*
Chaminade, R., 136, 151, 152, *160*
Chandler, R. F., Jr., 12, 13, 15, *90*, 118, 124, 125, *160*
Chang, C. W., 118, 124, 125, 155, *160*
Charriou, A., 117, *160*
Chevalier, A., 42, 78, 82, *87*
Chilton, S. J. P., 228, *241*
Chisholm, A. T., 231, *241*
Chitwood, B. G., 244, 247, 250, *263*
Christie, J. R., 247, *263*
Clark, F. E., 153, *160*
Clark, G. L., 24, 25, 34, *87*
Clark, H. E., 259, *263*
Clarke, E. J., 149, *164*
Clayton, E. E., 248, *263*
Clements, Frederic E., 199, *241*
Cline, M. G., 8, 13, *87*
Clark, Noble, 278, 295, *320*
Cole, J. S., 58, 63, *87*

Coleman, N. T., 17, 19, *87*, 141, *160*
Coleman, O. H., 101 (see Weihing), 103 (see Weihing), 108 (see Weihing), *112*
Coles, J. S., 301, *319*
Collander, R., 148, *161*
Collier, J. W., 307, *319*
Compton, L. L., 292, *322*
Comstock, V. E., 107, *110*
Conner, A. B., 281, *320*
Copley, T. L., 277, 280, 283, 288, *320*
Cox, M. B., 283, 285, 286, 288 (see Daniel), 291, *320*
Crafts, A. S., 109, *110*
Craig, N., 16, 42, *87*
Crickman, C. W., 305, *305*
Crockett, S. C., 308, *321*
Cromer, G. W., 115, *159*
Crown, R. M., 225 (see Shealy), *241*
Cullinan, S. J., 127, 137, *164*
Cutler, J. S., 94 (see Willard), 95 (see Willard), 97 (see Willard), 99 (see Willard), 100 (see Willard), 102, (see Willard), 103 (see Willard), 104 (see Willard), 106 (see Willard), 107 (see Willard), 108 (see Willard), *112*

D

Daniel, H. A., 283, 285, 288, 291, 292, *320*
Darland, R. W., 34, 81, *91*
Darlington, C. D., 211, *240*
Davies, J. G., 227, *240*
Davol, F. D., 17, 18, 20, 41, 57, 82, *88*
Dawson, J. R., 94, 100, 101, 107, *110*
Dean, L. A., 18, 20, 22, 24, *87*, *89*
Deming, J. M., 140, *160*
Demortier, G., 68, *87*
Denison, I. A., 121, *161*
Denny, C. S., 44, *87*
Desai, A. D., 24, 27, *87*
De Turk, E. E., 126, 127, 129, 131, 134, 135, 136, 141, *160*, *161*, *164*
De Vane, E. H., 211, 230, *240*
Dexter, S. T., 107, *110*
Dickson, R. E., 281, 285, 298, *320*
Diebold, C. H., 56, 60, *90*
Diseker, E. G., 301, *320*
Doetsch, J. H., 153, *159*
Doieinko, A. O., 120, *163*
Domingo, C. E., 280, *320*
Dorrance, A. B., 99, *111*
Dotzenko, Alex, 107, *110*
Douglass, Earl, 96, *110*
Drake, M., 83, *87*, 118, 126, *161*
Dreibelbis, F. R., 50, 60, *89*
Drosdoff, M., 21, 28, 29, 30, 56, 73, *87*
Dubois, J., 42, *87*
Duley, F. L., 278, 287, 288, 293, 297, *320*
Dunnewald, T. J., 294, *322*
du Preez, J. W., 40, 41, 42, *87*
Dutilly, A., 8, 51, *87*
Dyal, R. S., 17, 19, 21, 73, *87*, *91*, 134, 138, *161*
Dyer, B., 135, *161*

E

Edgington, G., 13, 17, *87*
Edwards, M. J., 47, 75, *87*
Ehrenberg, P., 144, *161*
Eisenmenger, W. C., 118, 120, *162*
Eke, Paul, 306, *320*
Ellis, B. S., 32, *91*
Ellison, W. D., 287, *320*
Elwell, H. M., 283, 285, 288, (see Daniel), 291, *320*
Ely, J. B., Jr., 55, *89*
Eno, C. F., 153, *161*
Ensminger, L. E., 17, 19, 25, 33, 35, 39, *89*
Erb, E. S., 135, *161*
Etheridge, W. C., 108, *110*
Evans, C. E., 124, 125, 126, 128, 137, *161*
Evans, D. D., 75, 76, *88*
Evans, R. E., 94 (see Woodman), 96 (see Woodman), 101 (see Woodman), 107 (see Woodman), *112*

F

Feher, D., 154, *161*
Feustel, I. C., 8, 51, *87*
Fielder, V. B., 306, *320*
Fine, L. O., 137, 142, *161*
Finnell, H. H., 284, 292, 307, *320*
Fireman, M., 152, 157, *160*, *161*

Fisher, C. E., 285 (see Dickson), 298, *320*

Fisher, H. S., 239, *241*

Fitts, J. W., 32, *87*

Fitzpatrick, E. G., 34, *87*

Forrest, L. A., 277 (see Copley), 280 (see Copley), 288 (see Copley), *320*

Forsling, D. L., 288, *319*

Forster, G. W., 309, *320*

Fortman, H. R., 230, *240*

Foster, Z. C., 19, 36, *87*, *90*

Frank, M., 154, *161*

Franzke, Clifford, 101 (see Hume), *111*

Fraps, G. S., 121, 123, 129, *161*

Frear, W., 135, *161*

Free, G. R., 75, *87*, 293, 301, *320*

Frei, E., 13, *87*

Fry, W. H., 121, *161*, *162*

Fujimoto, C. K., 19, 21, *86*, *90*, 158, *160*

**G**

Gaines, J. G., 248 (see Clayton), *263*

Gaiser, R. N., 56, *87*

Garber, R. J., 223, 234, *240*, *241*

Gardner, J. L., 297, *321*

Gardner, R., 101 (see Weihing), 108 (see Weihing), *112*

Garman, W. L., 20, *87*

Garver, Samuel, 99, 108, 109, *110*

Gautier, E. F., 28, *88*

Gedroiz, K. K., 117, 123, *161*

Geise, F. W., 122, *164*

Getty, R. E., 222, *241*

Gholston, L. E., 124, 125, *161*

Gieseking, J. E., 12, 88, 131, 136, 145, *163*, *164*

Gile, P. L., 121, *161*

Gilligan, G. M., 149, *161*

Gisiger, L., 150, *161*

Glass, J., 295 (see Browning), *319*

Godbole, S. V., 229, 232, *241*

Godfrey, G. H., 246, *263*

Goldich, S. S., 18, 20, 42, 70, *86*, *88*, 121, *161*

Goldschmidt, V. M., 122, *161*

Gorbunov, N. I., 121, *161*

Gouny, P., 148, *161*

Gow, P. L., 158, *161*

Graber, L. F., 97, 98, 101, 102, 104, 105, 106, *110*

Graham, E. R., 122, 135, *161*

Graham, T. W., 248 (see Clayton), *263*

Grandfield, C. O., 54, 63, *88*, 97, 98, 99, 103, 109, *110*, *111*

Granovsky, A. A., 104, *111*

Graves, R. R., 94 (see Dawson), 100 (see Dawson), 101 (see Dawson), *110*

Griffith, E., 101, *111*

Griffith, G., 22, *88*

Grim, R. E., 132, 133, 134, *161*

Griswold, F. S., 81, *89*

Gruner, J. W., 152, *161*

Guennelon, R., 121, *160*

Gustafson, A. F., 278, 284, 293 (see Free), 301 (see Free), *320*, *321*

**H**

Hackleman, J. C., 101 (see Burlison), 103 (see Burlison), 108 (see Burlison), *110*

Haddock, J. L., 12, 24, *90*

Halais, P., 16, 42, *87*

Hagihara, H. H., 21, *86*

Hanson, H. C., 297, *322*

Hardy, F., 32, *88*

Harper, Horace J., 280, 285, 304, *320*

Harper, W. G., 44, 45, *88*

Harrison, C. M., 106, *111*

Hartman, W. A., 275, *320*

Hartwell, B. L., 120, *161*

Hasson, J., 248, *263*

Hauge, S. M., 96, *111*

Hays, O. E., 278, 285, 288, 295, 301, *320*

Headley, F. B., 105, *111*

Hearn, W. E., 5, 17, 39, 40, 47, *88*

Hein, M. A., 220, 234, *241*

Hellman, N. N., 133, 134, 138, 140, *162*

Helm, C. A., 108, *110*, 293, *321*

Henderson, W. J., 157, *161*

Hendricks, S. B., 114, 133, 134, 138, 155, *159*, *161*, *163*

Hendricks, S. J., 12, 24, 29, *86*

Hendrickson, A. H., 57, 58, 76, *88*, *91*

Hendrickson, B. A., 278, 281, 287, *321*

Henin, S., 121, 134, 140, *160*

Henley, W. W., 203, 215, *241*

Henson, Paul R., 101, 108, *111*

Hester, J. B., 147, *161*
Heusinkveld, David, 103 (see Burlison), *110*
Hildebrand, S. C., 106, *111*
Hill, Geo. R., 98, 100, *112*
Hill, H. H., 145, *164*
Hill, H. O., 283, 301, *321*
Hitchcock, A. S., 216, *241*
Hoagland, D. R., 115, 118, 124, 125, 135, 138, 141, 155, *161*, *163*
Hockensmith, R. D., 296, *321*
Hoffer, G. N., 74, 78, 79, *88*
Hofmann, V., 134, *163*
Hogg, P. G., 234, 235, *241*
Hollowell, E. A., 104, *111*
Hollstein, W., 16, *88*
Holmes, R. S., 5, 12, 17, *87*, *88*, 118, 126, 131, 135, 142, 149, *163*
Hoover, C. D., 124, 125, 131, *161*
Hoover, M. D., 66, 75, 76, 79, *88*
Hopkins, G. G., 123, *161*
Hopkins, H. T., 155, *162*
Horner, G. M., 279, 283, *321*
Horton, R. E., 287, *321*
Hough, J. G., 17, 19, 20, *88*
Hubbard, D. S., 297, *321*
Hubbard, E. H., 17, 45, *88*
Huberty, M. R., 74, *88*
Humbert, R. P., 37, 38, 39, 57, *89*
Hume, A. N., 77, *88*, 101, *111*
Hunter, A. S., 147, *162*
Hunter, A. W. S., 211, *241*
Hurcombe, R., 212, *241*
Hurwitz, C., 154, *162*
Hutton, C. E., 23, 24, 25, 26, 29, *88*

I

Issak, P., 32, *88*

J

Jackobs, J. A., 96, 99, 100, 101, 105, *111*,
Jacks, G. V., 285, 309, *321*
Jackson, M. L., 17, 19, *87*, 120, 132, 133, 134, 138, 140, 141, *160*, *162*
Jacob, E., 158, *162*
Janaki Ammal, E. K., 211, *240*
Janssen, G., 118, 126, 135, *160*
Jarusov, S. S., 118, *162*
Jefferson, M. E., 133, *161*
Jenkins, C., 17, 45, *88*
Jenny, H., 27, 48, 75, 80, *88*, *89*, 115, 130, 142, 144, 145, 146, 151, *162*
Jensen, V., 247, *264*
Jewett, H. H., 104, *111*
Joffe, J. S., 138, 152, 156, *162*, 296, *321*
Johnson, E., 122, *161*
Johnson, Howard J., 104, *111*
Johnson, M. O., 246, *263*
Johnson, P. R., 278 (see Pope), *322*
Jones, Fred R., 104, 106, *111*
Jones, G. D., 227, *241*
Jones, R. J., 83, *88*, 138, *164*
Jones, U. S., 155, 161, *161*, *162*
Joy, Edgar, 101 (see Hume), *111*

K

Kachinsky, N. A., 75, *88*
Kandasamy, A. P., 49, *88*
Kanehiro, Y., 118, 124, 129, *160*
Karper, R. E., 231, *241*
Katterman, G., 234, *241*
Keen, B. A., 76, *90*
Kell, W. V., 300, *321*
Kelley, W. P., 35, *88*, 136, *162*
Kellogg, E. C., 6, 8, 10, 11, 15, 16, 17, 18, 20, 32, 33, 35, 36, 39, 40, 51, 57, 64, 65, 69, 82, *86*, *88*, *91*
Kelly, J. B., 151, *164*, 297, *321*
Kelly, L. L., 287, *320*
Keyes, M. G., 115, *159*
Kidder, D. H., 58, 60, *88*
Kidder, E. H., 284 (see Van Doren), *322*
Kiesselbach, T. A., 94, 95, 101, 103, 105, 107, 108, *111*
Killinger, G. B., 225 (see Blaser), 229 (see Blaser), *240*
Kime, C. D., Jr., 157, *162*
Kincaid, R. R., 259, *263*
King, W. A., 219 (see La Master), *241*
Kirk, W. G., 225 (see Shealy), *241*
Kirkham, D., 58, 59, 60, *88*
Klingebiel, A. A., 59, 79, 81, *91*
Knight, A. T., 56, *88*, *91*
Kolodny, L., 137, 156, *162*
Kopland, D. V., 94 (see Dawson), 100 (see Dawson), 101 (see Dawson), *110*

Koszeleskis, A., 153, *162*
Kreutzer, W. A., 247, *263*
Kryopoulos, S., 154, *162*
Kubota, J., 6, 8, 29, *89*
Kuhn, J., 246, *263*
Kutish, F. A., *306, 321*

L

Lachower, D., 115, *162*
La Master, J. P., 219, *241*
Lamb, J., 75, *87*
Lamb, John Jr., 284, 293, (see Free), 301 (see Free), *320, 321*
Langley, B. C., 285 (see Dickson), 298, *320*
Larson, W. E., 23, 24, 34, *88*, 128, 143, *162*
Latham, E. D., 287 (see Peele), *321*
Law, A. G., 107, *110*
Laws, W. D., 75, 76, *88*
Lawton, K., 56, *88*, 156, *162*
Leahey, A., 8, *88*
Lear, B., 247, *263*
Lee, Alvin T. M., 305, *321*
Lee, C. K., 128, *162*
Leenheer, L. de, 122, *162*
Lehmann, W., 124, 125, *164*
Leighty, W. J., 37, 47, *89*
Leonard, C. D., 27, *88*
Lunkel, W. A., 97 (see Graber), 98 (see Graber), 101 (see Graber), *110*
Levine, A. K., 138, 152, *162*
Lewis, C. C., 118, 120, *162*
Lewis, R. D., 106 (see Thatcher), *112*
Lilienthal, David, 271, *321*
Lilleland, O., 125, 149, 158, *162*
Lipman, J. G., 122, *162*
Litardiere, R. De, 237, *241*
Little, S., 55, *89*
Livezey, Walter, 102 (see Bachtell), 107 (see Bachtell), *110*
Loehwing, W. F., 155, *162*
Lohse, H. W., 14, *89*
Loomis, W. E., 155, *160*
Lovvorn, R. L., 216, 217, *241*
Lunt, H. A., 11, 14, *89*
Lutz, J. F., 33, 55, 81, *89*, 277 (see Copley), *320*
Lyford, W. H., 10, 11, 39, 40, *89*
Lyon, T. L., 144, *162*
Lyons, E. S., 32, *87*
Lytle, W. F., 58, 60, *88*

M

McBeth, C. W., 212 (see Burton), *240*, 247, 249, *263*
McCall, A. G., 278 (see Pope), 279, 280 (see Copley), 282 (see Smith), 283, 287 (see Borst), 288 (see Copley), 294 (see Smith), 297 (see Borst), 301 (see Smith, Hill, Hays), *319, 320, 321, 322*
McCalla, T. M., 155, *162*
McCampbell, C. W., 94 (see Salmon), 101 (see Salmon), 102 (see Salmon), 103( see Salmon), 107 (see Salmon), *111*
McCaughey, W. J., 121, *162*
McClelland, J. E., 121, 149, *162*
McDole, G. R., 71, 72, 84, *86*
McGee, W. J., 274, *321*
McGeorge, W. T., 150, *162*
MacGregor, J. M., 30, 33, 35, *89, 90*
McGrew, P. C., 295, 308, *322*
McGuire, W. S., 96, *111*
MacIntrie, W. H., 144, 145, *162, 164*
McKay, H. C., 291, *321*
Mackenzie, A. J., 19, *86*
Mackenzie, R. C., 12, 17, *89*
McKibben, R. R., 14, *90*
Mackie, W. Z., 133, *162*
McLean, E. O., 147, *162*
McNall, P. E., 306, *319*
McVickar, M. H., 227 (see Jones), *241*
Maegdefrau, E., 134, *163*
Magistad, O. C., 124, *159*
Magnus, G., 119, *163*
Malcolm, J. L., 124, 125, *160*
Mann, H. H., 144, *163*
Marbut, C. F., 13, 14, 15, 16, 17, 19, 22, 25, 26, 27, 29, 33, 38, 39, 41, *89*, 114, 156, *163*
Mark, J. J., 98, *111*
Marshall, C. E., 34, 91, 117, 118, 133, 147, *163*
Martin, I. L., 17, 19, 35, *87, 91*
Martin, J. C., 115, 118, 124, 125, 135, 138, 141, 155, *161, 163*

Mathews, A. C., 200, 203, *240*
Matsusaka, Y., 18, 21, *89*
Matthews, D. J., 246, *263*
Matthews, O. R., 58, 63, *87*
Matzek, B. L., 17, 45, *88*
Mayton, E. L., 217, *241*
Mazoyer, R., 148, *161*
Megee, C. R., 98 (see Silkett), *111*
Mehlich, A., 17, 19, *87*, 141, 144, 145, *160*, *163*
Merkle, F. G., 287, *319*
Merrill, L. P., 291, *321*
Merwin, H. D., 123, 142, 149, *163*
Metzger, W. H., 54, 63, *88*
Meyer, L., 157, *163*
Midgley, A. R., 297, *321*
Miller, M. F., 278, 287, 294 (see Smith), 311, *320*, *321*
Milne, A., 141, *164*
Mitchell, J. H., 219 (see La Master), *241*
Mitchell, R. L., 15, 22, 23, 25, 26, 29, 32, *89*
Mohr, E. C. J., 16, *89*
Montagne, J. T. W., 247, *263*
Moon, J. W., 17, 19, 54, *86*, *89*
Monteith, J., 104, *111*
Moore, L. A., 96, *111*
Moore, R. A., 102, *111*
Morgan, G. W., 301, *319*
Mortland, M. M., 131, 136, *163*
Mosier, J. G., 278, *321*
Moss, H. C., 22, 32, *89*
Moss, W. A., 291, *321*
Motheral, J. R., 308, *321*
Muir, A., 24, *89*
Mukherjee, J. N., 32, *89*
Munsell, R. I., 94, 98, 99, 101, 104, 105, *110*
Murphy, F. T., 225 (see Takahashi), *241*
Musgrave, R. B., 107
Musgrave, G. W., 289, 295, *321*
Musser, R. H., 306, *321*
Myers, H. E., 54, *89*
Myers, W. M., 223, 227, 228, *241*

**N**

Nagelschmidt, G., 24, *89*, 133, *163*
Neal, O. R., 280, 294, *321*
Neller, J. R., 248, *263*
Nelson, L. B., 62, *90*
Nelson, Martin, 99, 101, *111*
Nelson, N. T., 97, 98 (see Graber), 101 (see Graber), *111*
Nelson, Peter, 297, 305, *321*, *322*
Nelson, R. A., 12, 24, 29, *86*, 114, 138, *159*, *161*
Newhall, A. G., 247, *263*
Nichols, M. L., 282, *321*
Nielsen, Etlar L., 209, 223 (see also Ahlgren), *241*
Nikiforoff, C. C., 8, 28, 29, 37, 38, 39, 43, 45, 51, 57, *89*
Nilsson, F., 228, *241*
Norman, D. B., 94 (see Woodman), 96 (see Woodman), 101 (see Woodman), 107 (see Woodman), *112*
Norton, E. A., 275, *321*
Norton, R. A., 156, *160*, 282, 289, 293, 295, *319*, *321*
Nostiz, A., 117, *163*
Nowosad, F. S., 94 (see Armstrong), *110*
Nutt, G. B., 292, *321*
Nygard, I. J., 8, 51, *88*

**O**

Oakes, H., 22, 24, 47, *89*
Odell, R. T., 60, *89*
Odynsky, W., 26, 32, *89*
Olmstead, L. B., 78, 81, *89*
Olsen, C., 148, *163*
Olsen, S. R., 123, *163*
O'Neal, A. M., 276, *321*
Orvedal, A. C., 6, 8, 29, *89*
Oskamp, J., 56, *89*
Overstreet, R., 115, 138, 155, *162*, *163*
Owen, C. R., 218, *241*

**P**

Page, H. J., 123, 139, 141, 152, *163*
Page, J. B., 78, 79, 82, *89*, 279, *321*
Palmer, V. J., 285, 286, *320*
Parish, C. L., 295 (see Browning), *319*
Parham, S. A., 219 (see Burton), *240*
Parker, E. R., 75, *89*
Partridge, N. L., 280, *321*
Pauling, L., 133, *163*

Pearson, R. W., 13, 14, 17, 19, 25, 26, 33, 35, 39, 73, 85, *89*
Peech, M., 118, 124, 125, 130, 142, 146, 152, *160*, *163*
Peele, T. C., 287, 292, *321*
Peevy, W. J., 283, 301 (see Hill), *321*
Pember, F. R., 120, *161*
Pepkowitz, L. P., 155, *163*
Pendleton, R. L., 40, 41, 57, 70 *89*
Pennington, R. P., 114, 133, 134, *162*, *163*, 230 (see Fortman), *240*
Peterson, J. B., 12, 25, *89*
Peterson, M. J., 305, *322*
Peterson, R., 297, *322*
Pierre, W. H., 14, 26, 73, 85, *89*, 150, 151, 152, *159*, *160*, *164*, 279, *322*
Pillai, V. Gonathinayagam, 231 (see Ayyanger), *240*
Plummer, J. K., 121, 122, *163*
Pohlmann, G. S., 83, *89*
Poos, F. W., 104, *111*
Pope, J. B., 278, *322*
Portz, L. C., 110 (see Viehmeyer), *112*
Posey, W. B., 283, *320*
Powers, W. L., 61, *89*
Post, F. A., 50, 60, *89*
Prianischnikov, D. N., 120, *163*
Prince, A. L., 124, 125, *160*
Purvis, E. R., 137, *160*

**R**

Ramig, R. E., 110 (see Viehmeyer), *112*
Ramser, C. E., 281, *322*
Ramsey, A. A., 101, *111*
Rather, H. C., 98 (see Silkett), 99, *111*
Rathlef, H. von, 40, *90*
Raynor, R. N., 109, *111*
Ree, W. O., 286, *322*
Reitemeier, R. F., 115, 118, 124, 125, 126, 129, 131, 135, 137, 142, 149, 152, *160*, *163*
Renszer, H. W., 153, *161*
Reuther, W., 125, *164*
Reynolds, D. H., 24, 25, 34, *87*
Rhoades, H. F., 23, 24, 32, 33, 34, 35, *87*, *88*, *90*
Rice, T. D., 33, 35, *87*
Richard, J. A., 12, 13, 15, *90*
Riecken, F. F., 14, 22, 23, 24, 25, 26, 27, 29, 33, 34, 35, 60, 73, *89*, *90*, *91*
Ripley, P. O., 94 (see Armstrong), *110*
Ripperton, J. C., 224, 225, (see Takahashi), *241*
Ritchey, Geo. E., 203, 215, 225, 228, *241*
Robbins, W. R., 137, *162*
Roberts, Edd., 273, *322*
Roberts, Ray C., 16, 17, 39, 40, 42, 47, 69, *90*
Robertson, D. W., 101 (see Weihing), 103 (see Weihing), 108 (see Weihing), *112*
Robinson, B., 144, *162*
Robinson, D. O., 140, *160*
Robinson, G. W., 22, *90*
Rockie, W. A., 295, 308, *322*
Rodrigues, G., 33, *88*
Rogers, H. T., 83, 88, 147, 149, 150, *163* *164*
Rogler, Geo. A., 203, *241*
Roller, E. M., 153, *159*
Rose, Dorothy, 107 (see Dexter), *110*
Rose, L. E., 34, *87*
Ross, C. S., 133, *163*
Rost, C. O., 25, 32, 35, 68, 71, 72, 83, 84, *86*, *87*, *90*
Rouse, R. D., 127, 129, 134, *163*
Ruhnke, G. N., 14, *89*
Russel, J. C., 288, 293, 297, *320*
Russell, E. J., 243, *263*
Russell, E. W., 12, 76, *90*
Russell, M. B., 24, *90*

**S**

Salmon, S. C., 94, 101, 102, 103, 107, *111*
Sauer, W. L., 284, 307, *322*
Saunders, K. B., 144, *162*
Scarseth, G. D., 83, *90*, 118, 126, *161*
Schachtschabel, P., 117, 118, 124, 125, 126, *163*
Schneider, R., 157, *163*
Schoenman, L. R., 36, *87*
Schokalsky, Z. J., 28, *90*
Schultz, H. K., 228, *241*
Schuster, C. E., 34, 56, *90*
Scoates, D., 281, *320*
Scofield, C. S., 331, 343, *344*
Searls, E. M., 104, *111*

Sears, O. H., 101 (see Burlison), 103 (see Burlison), 108 (see Burlison), *110*
Sears, Paul B., 266, *322*
Seatz, L. F., 128, *163*
Seay, W. A., 118, *164*
Sell, O. E., 210, *240*
Shade, E. R., 144, 145, 146, *162*
Sharasuvona, S., 40, 41, 57, 70, *89*
Shaw, B. T., 123, 144, 145, *162*, *163*, *164*
Shaw, G. T., 14, *90*
Shaw, Warren C., 109
Shealy, A. L., 225, *241*
Sheldon, W. H., 107 (see Dexter), *110*
Shelton, F. A., 147, *161*
Shepard, Ward, 288, *322*
Sherman, G. D., 16, 17, 18, 19, 21, 27, 40, 41, 42, 47, 57, 69, 70, *89*, *90*, *91*
Shive, J. W., 155, *163*
Silkett, V. W., 98, *111*
Simon, R. H., 124, 128, *161*
Simonson, R. W., 13, 16, 26, 34, 59, 80, *86*, *89*, *90*
Sirur, S. S., 22, *86*
Smith, A. L., 259, *263*
Smith, B. W., 218, *241*
Smith, D., 106, *111*
Smith, D. C., 223 (see also Ahlgren), *241*
Smith, D. D., 77, 83, *92*, 282, 286, 294, *322*
Smith, F. F., 104, *111*
Smith, G. D., 14, 22, 23, 24, 25, 26, 27, 32, 35, 49, 65, 73, *90*
Smith, H. M., 6, 8, 29, *89*
Smith, H. V., 39, 44, 45, *86*
Smith, H. W., 33, 34, 35, *90*
Smith, L. H., 44, 45, *88*
Smith, R. M., 37, 38, 58, *90*
Smith, R. S., 25, 26, 77, *90*, *91*
Smith, T. E., 248 (see Clayton), *263*
Smith, T. J., 227 (see Jones), *241*
Snyder, W. W., 96, *111*
Sotola, J., 94, 96, 105, *111*
Southern, J. H., 308, 310, *322*
Southwell, B. L., 203, 204, 211, 219 (see Burton), *240*
Specht, A. W., 155, *162*
Spaeth, J. N., 56, 60, *90*
Sprague, V. G., 98, 104, *110*, *111*, 223, *241*
Spry, R., 14, 26, 73, 85, *89*
Spuy, M. J., 94, *111*
Stalwick, A. E., 33, 34, 35, *90*
Stanford, G., 62, 90, 139, 149, 151, 152, *164*
Stapledon, R. G., 228, *241*
Stark, F. L., 246, 247, *263*
Staten, Glen, 100, 101, 108, *111*
Stauffer, R. S., 24, 52, 79, *90*, 284 (see Van Doren), 293, *322*
Stead, H. A. J., 94, *111*
Steele, J. F., 296, *321*
Steiner, G., 244, 245, *263*
Stephens, C. G., 32, 41, *90*, *91*
Stephens, J. L., 203, 204, 212 (see Burton), 215, 219 (see Burton), 230, *241*
Stephenson, R. E., 34, 56, *90*
Stephenson, R. R., 154, *164*
Stewart, E. H., 83, *87*, 124, 125, *164*
Stewart, R., 125, *164*
Stobbe, P. C., 36, 38, *90*
Stoeckeler, H., 302, 303, *322*
Stokes, W. E., 213, 225, (see Blaser), 229 (see Blaser), *240*
Stoliarova, A., 117, *164*
Storie, R. E., 32, *90*
Stroud, R. S., 100 (see Staten), 101 (see Staten), 108 (see Staten), *111*
Sturgis, M. B., 137, *164*
Sturkie, D. G., 239, *241*
Sudds, R. H., 54, 56, *87*
Swanson, C. O., 94 (see Salmon), 101 (see Salmon), 102 (see Salmon), 103 (see Salmon), 107 (see Salmon), *111*
Sweet, A. T., 54, 56, 57, 74, *90*

T

Takahashi, M., 101, *112*, 118, 124, 129, *160*, 224, 225, *241*
Tam, R. K., 259, *263*
Tamm, O., 39, *90*
Taylor, A. L., 247, 249, *263*
Taylor, Carl C., 266, *322*
Taylor, E. M., 49, *90*
Templin, E. H., 17, 19, 35, *87*, *91*
Thatcher, L. E., 94 (see Willard), 95 (see Willard), 97 (see Willard), 99

(see Willard), 100 (see Willard), 102 (see Willard), 103 (see Willard), 104 (see Willard), 106 (see Willard), 107 (see Willard), 108 (see Willard), *112*
Thiel, G. A., 27, *91*
Thomas, George, *344*
Thomas, Moyer D., 98 100, *112*
Thompson, C. R., 96, *112*
Thompson, G., 297, *321*
Thomson, W. A., 49, 50, 51, *91*
Thorne, G., 247, *264*
Thornton, S. F., 125, *164*
Thorp, J., 10, 13, 15, 22, 24, 28, 32, 39, 40, 41, 47, *86*, *87*, *89*, *91*
Throckmorton, R. I., 109, *111*, 291, *322*
Tiedjens, V. A., 83, 84, *91*
Tobiska, J. W., 96 (see Douglass), *110*
Todd, F. A., 248 (see Clayton), *263*
Torsell, R., 99, *112*
Toth, S. J., 147, 149, *160*, *162*
True, R. H., 122, *164*
Truog, E., 118, 120, 129, 138, 142, *161*, *162*, *164*
Tucker, E. A., 305, *322*
Turnage, W. V., 49, *91*
Turpin, H. W., 100, 101, *112*
Tyler, J., 249, *264*
Tyner, E. H., 118, 120, *164*
Tysdal, H. M., 102, 103, 105, 108, 109, *112*

**U**

Uhland, R. E., 278, 287, *322*
Ulrich, R., 26, 33, 34, 35, 57, 64, 65, 70, *91*

**V**

Vail, C. E., 96 (see Douglass), *110*
Vandecaveye, S. C., 154, *164*
Van der Merwe, C. R., 22, 24, 25, 26, 27, 69, 73, 83, 84, *91*
Van Doren, C. A., 59, 79, 81, *91*, 284, 293, *322*
Van Doren, Mark, 199, *241*
Van Horn, D. L., 226, *241*
Van Itallie, T. B., 119, 148, *164*
Vazhenin, I., 136, *164*
Veatch, J. O., 36, *87*
Veihmeyer, F. J., 57, 58, 76, *91*
Vessel, A. J., 22, *91*
Viehmeyer, Glenn, 110, *112*
Viets, F. G., Jr., 148, *164*
Vijiaraghaven, C., 231 (see Ayyanger), *240*
Vilensky, D. G., 32, *91*
Vinall, H. N., 220, 222, 234, *241*
Volk, G. M., 259, *263*
Volk, G. W., 131, 136, 149, *164*
Volk, N. J., 118, 124, 125, 135, 149, 157, 158, *164*

**W**

Walker, G. F., 13, *91*, 122, 134, 141, *164*
Walker, R. K., 137, *164*
Walsh, T., 127, 137, 149, *164*
Walter, David H., 300, *322*
Wascher, H., 24, 47, *91*, *92*
Washko, J. B., 230 (see Fortman), *240*
Watkins, W. I., 22, 32, *91*
Watson, A. J., 110, *112*
Wear, J. I., 139, 152, *164*
Weaver, John E., 199, *241*
Weissmann, H., 124, 125, *164*
Weitz, B. O., 65, *91*
Weaver, J. E., 34, 55, 75, 81, *91*
Wehrwein, G. H., 308, *322*
Weihing, R. M., 101, 103, 108, *112*
Weitzell, E. C., 308, 309, *322*
Westin, F. C., 61, *91*
Westover, H. L., 101, 102, 103, 104, 108, 109, *110*, *111*
White, J. L., 134, 139, 152, *164*
Whiteside, E. P., 5, 25, 26, 32, 33, 34, 35, *91*
Whitman, W., 297, *322*
Whitson, A. R., 294, *322*
Whitt, D. M., 282 (see Smith), 294 (see Smith), 301 (see Smith), *322*
Whyte, R. O., 285, 309, *321*
Wiklandee, L., 140, 145, 149, *164*
Wilcox, J. C., 56, *91*
Willard, C. J., 78, 79, 82, *89*, 94, 95, 97, 98, 99, 100, 102 (see Bachtell), 103, 104, 105, 106, 107, 108, 109, *110*, *112*, 279, *321*
Williams, B. H., 22, 32, *91*

Williams, R. A., 302, 303, *322*
Williams, W., 123, 141, *163*
Wilsie, C. P., 101, *112*, 224, *241*
Wilson, H. A., 58, 60, 78, 81, *91*
Wilson, H. M., 284, *321*
Wing, Joseph E., 98, 100, 102, 103, 108, *112*
Winters, E., 24, 36, 37, 38, 47, *91*, *92*
Winters, F., 128, *163*
Winters, R. K., 308, *322*
Wood, L. K., 126, 129, 131, 134, 135, 136, 141, *161*, *164*
Woodburn, R., 289, *319*
Woodhouse, W. W., Jr., 227, *241*
Woodman, H. E., 94, 96, 101, 107, *112*
Woodruff, C. M., 77, 83, *92*, *93*
Wooten, H. H., 275, *320*
Worzella, W. W., 291, *322*
Wyatt, F. A., 30, 33, 35, 37, 47, *89*, *90*

**Y**

Yeager, A. F., 82, *92*
Yoder, R. E., 301, *320*
York, E. T., 116, 124, 136, 137, 149, 150, 151, 154, *164*
Youngs, F. O., 44, *92*
Young, J. B., 144, *162*

**Z**

Zingg, A. W., 282 (see Smith), 289, 294 (see Smith), 301 (see Smith), *322*

# Subject Index

A

Agricultural Adjustment Administration, 271, 277
Agriculture in England and Wales, 165-196
Agriculture in England and Wales,
  acre yields, 182
  animal production, 170-174
  background, 165-167
  crop production, 168-170
  education, 174-176
  farm buildings, 194, 195
  land use, 179-183
  livestock numbers, 183
  mechanization, 168, 169, 180
  policy, 186-188
  recent developments, 189-192
  technical advances, 192-194
  wartime production, 176-179
Albite, 121
Alfalfa, 27, 54, 55, 56, 58, 60, 63, 71, 73, 77, 80, 118, 120, 125, 128, 147, 279, 285, 294
  times of cutting, 102-103
Alfalfa-grass mixtures, 107
Alfalfa hay, carotene content, 96
  fiber content, 96
  mineral content, 96
  protein content, 95
Alfalfa meadows, 93-112
  cutting recommendations, 107-108
  cutting systems, 94-102
  fall cuttings, 98-100
  management, 93-112
  weed control, 109-110
Alfalfa roots, food reserves, 97-98, 100, 101
Alluvial soils, 16, 46, 63, 76, 324
Allyl bromide, 247
Alsike clover, 120, 123
Altafescue, 280
Amberlite resin, 146
Ammonium fixation, 151-153
Annual ryegrass, 211
Anorthite, 121
Anorthoclase, 121
Apomixis, 208, 218, 238
Apples, 54, 56, 57, 74
*Aspergillus niger*, 153, 154
Augite, 121
*Avena sativa*, 54
*Axonopus affinis*, 213, 214

B

*Bacillus extorquens*, 153
Bahia grass, 200, 203, 204, 206-209, 229
*Barbarea barbarea*, 109
Barley, 145, 148, 153
Bauxite, 70
Beans, 148, 149
Beidellite, 132, 133, 134, 139
Bentonite, 121, 137, 138, 139, 140, 149, 152
Bermuda grass, 200, 202, 203, 204, 207, 209-213, 214, 216, 229, 238, 239, 286
Biotite, 114, 120, 121, 122, 132, 153
Bluegrass, 54, 286
Bromegrass, 223, 226, 236, 237
*Bromus secalinus*, 109
*Bromus tectorum*, 109
Brown podzolic soils, 6, 8, 10, 12, 13, 14, 15, 46, 72, 82
Brown soils, 27, 28, 29, 30, 32, 44, 46, 50
Buckwheat, 120, 126, 151
Buffalo grass, 286
Bureau of Reclamation, 329-331, 334, 338, 342
Bitter winter cress, 109

C

Calcipans, 44
Calcite, 17, 29, 44
Caliche, 43-45
Carbon bisulfide, 253
Carbon tetrachloride, 247, 252
Carpet grass, 200, 207, 210, 213-214
Carrots, 126

Centipede grass, 202, 203, 204, 214-216
Cheat, 109
Chernozems, 22, 25, 26, 27, 28, 29, 30, 31, 32, 35, 46, 49, 50, 51, 80, 81, 82, 123, 143, 154
Chernozemic soils, B horizons, 21-27, 28
Chestnut soils, 22, 23, 25, 26, 27, 30, 32, 50, 75
Chick weed, 109
Chlorobromo propene, 247
Chloropicrin, 246, 247, 248, 251, 258, 259, 260
Civilian Conservation Corps, 268
Claypans, 5, 31-35, 54, 56, 57, 59, 60, 63, 67, 69, 80
*Clostridium pasteurianum*, 153
Cocksfoot, 226
Contour furrows, 298
Contour plowing, 270
Contour strip farming, 266, 267, 274, 278, 300-302, 304, 314, 317
Contour tillage, 267, 283, 284
Corn, 26, 54, 55, 56, 58, 60, 63, 64, 77, 82, 83, 85, 120, 137, 148, 151, 156, 198, 279, 280, 281, 292, 293, 294, 305
Cotton, 54, 58, 198, 278, 279, 280, 281, 295, 302, 305
  fusarium wilt, 259
  response to potash, 118
Crimson clover, 207, 210, 219
Crops, water requirements, 333
*Crotalaria lanceolota*, 200
*Cynodon dactylon*, 209, 211

D

*Dactylis glomerata*, 226
Daisy fleabone, 109
Dallis grass, 200, 201, 207, 210, 213, 214, 216-218, 229, 238, 286
Desert soils, 28, 29, 30, 32, 43, 80
Desertic soils, B horizons, 27-30
*Dianthus barbatus*, 148
Dichloropropane, 247, 252
Dichloropropene, 247, 252, 259, 260, 261
Dickite, 131
*Digitaria decumbens*, 228
Dinitro *o*-butyl phenol, 109
Downy brome grass, 109
Drainage, 270, 274

E

*Empoasca fabae*, 104
*Eremochola ophiuroides*, 214
*Ergeron annuus*, 109
Erosion, gully, 267, 275, 311, 313
  sheet, 267, 275, 313
  soil, 64, 65, 71, 72, 84, 85, 198
  soil losses, 277, 278, 279, 282, 295, 297
Erosion control, 265, 266, 267, 270, 271, 272, 274, 278, 289, 294, 308
  contour farming, 281-285
  cropping systems, 277-280, 294, 295
  terracing, 281-285
Ethylene dibromide, 247, 252, 254, 259, 260, 261
Ethylene dichloride, 247, 252

F

Feldspar, 117, 119, 120, 121, 122, 143
*Festuca arundinacea*, 236
Field peppergrass, 109
Flood control, 274, 289
Foxtail barley, 109
Fragipans, 5, 36-39, 54, 57, 58, 59, 60, 63, 77, 78

G

Gibbsite, 19
Goethite, 19
*Gossypium*, spp., 54
Grassed waterways, 274, 285-286
Grasses, evaluation, 201-205
Grasses for Southeastern States, 197-241
Gray-brown podzolic soils, 6, 8, 10, 12, 13, 14, 25, 31, 33, 35, 36, 50, 65, 67, 68, 69, 72
Gray desert soils, 27
Ground-water lateritic soils, 16, 31, 39, 41
Ground-water podzols, 31, 39, 40, 44, 57
Gypsum, 144

H

Hairy vetch, 280
Halloysite, 131
Hardpans, 5, 39-45, 54, 58, 63, 77, 78
*Helminthosporium sacchari*, 224, 225, 226
*H. sativum*, 208
Hematite, 19

*Heterodera*, 249, 260
*Hordeum distichum*, 148
*Hordeum jubatum*, 109
Hornblende, 121
Humic-gley soils, 8, 59, 79, 82
Hydrous mica, 114, 132, 133, 134, 140, 142

I

Illite, 12, 18, 19, 24, 34, 114, 116, 122, 132, 133, 134, 136, 139, 140
Infiltration rate, 287, 315
Inter-stratified minerals, 132, 142
Irrigation, 270, 274
  supplemental, 340-342
Irrigation agriculture, 61, 323-343
  area in U. S., 323-325
  Arkansas-White-Red river basin, 339-340
  Columbia river basin, 334-337
  early American, 325-327
  Missouri river basin, 338-339
  Mormon settlements, 327-328
  research needs, 342-343
Irrigation water, 332
Isomorphic substitution, 132, 139
Italian ryegrass, 218-220

J

Jack pine, 61
Johnson grass, 220-222

K

Kaolinite, 12, 18, 19, 25, 29, 39, 116, 117, 131, 132
Kentucky bluegrass, 218, 222-224, 227, 236
Kudzu, 286

L

Labradorite, 121
Ladino clover, 125, 126, 129, 130, 131, 149, 227, 236, 237
Land classification, 275-277, 313, 329
Laterite crusts, 40-43, 57, 67, 70
Laterites, 15
Latosolic soils, B horizons, 15-21
Latosols, 15, 16, 17, 20, 21, 39, 46, 52, 53, 67, 69, 72, 80, 82
*Lepidium campestre*, 109
Lespedeza, 54, 58, 210, 213, 216, 227, 279, 280, 286
*Lespedeza cuneata*, 57, 81
*L. sericea*, 280, 286
Lima beans, 147
Lime-potash law, 144
Loblolly pine, 56
Loess, 47, 59, 68, 294
*Lolium multiflorum*, 218
Lysimeters, 144

M

Maps, land use capability, 276
  soil, 275, 276
*Medicago sativa*, 27
*Melilotus*, spp., 26
Methyl bromide, 247, 250, 251, 255, 258, 259, 260
Microcline, 114, 120, 125, 153
Montmorillonite, 12, 18, 24, 34, 114, 117, 132, 133, 136, 138, 140, 141, 142
Mulch tillage, 271, 292, 301, 304
Muscovite, 114, 120, 121, 122, 132, 134, 135, 153
Mustard, 137

N

Nacrite, 131
Napier grass, 200, 201, 224-226
Nematodes, control in soil, 244-264
  plant parasitic, 244-246, 249
  reproduction rate, 249
  root-knot, 244, 245, 246, 249
*Nicotiana* spp., 54
Nontronite, 138

O

Oats, 54, 64, 120, 125, 126, 128, 148, 279
Olivine, 121
Orchard grass, 223, 226-228, 237
Orthoclase, 114, 120, 121, 144, 153
Ortsteins, 39, 40, 57
Over-grazing, 266, 271, 274, 297

P

Pangola grass, 200, 202, 228-229, 238
*Paspalum dilatatum*, 216

*P. malacophyllum*, 218, 238
*P. notatum*, 206-209
*P. urvillea*, 200, 218, 237
Peanuts, 147
Pearl millet, 226, 229-232
Peas, 120, 148
*Pennisetum glaucum*, 226, 229
*P. purpureum*, 224
Pentachlorophenol, 109
Permafrost, 50, 51
Phlogopite, 121, 132
*Pinus banksiana*, 61
*P. clausa*, 61
*P. strobus*, 54
*P. taeda*, 56
Plagioclase, 121
Planosols, 12, 31, 32, 33, 34, 35, 36, 37, 79, 81, 294
*Poa pratensis*, 54, 222
Podzolic soils, B horizons, 6-15
Podzols, 6, 8, 10, 12, 13, 15, 39, 46, 80, 82, 143
Potassium, soil, 113-164
Potassium fixation, 127, 135-141, 151-153
Potato leaf hopper, 104
Prairie soils, 22, 23, 24, 25, 26, 27, 31, 33, 34, 35, 63, 67, 68, 69, 72, 73, 81
Production and Marketing Administration, 271, 272, 299, 310
Pyrophyllite, 132

Q

Quartz, 29, 121

R

Rape, 120, 123
Reclamation, 271
Red clover, 79, 120, 123
Reddish Brown Lateritic soils, 15
Reddish Brown soils, 27, 28, 29, 30, 32, 44
Reddish Chestnut soils, 22, 23, 25, 26, 27, 32
Reddish Desert soils, 27, 44
Reddish Prairie soils, 22, 23, 25, 26, 27
Red-yellow Podzolic soils, 15, 16, 17, 18, 21, 32, 36, 39, 41, 52, 55, 56, 65, 69, 73, 75, 80
Regosols, 46
Rhizosphere, 153
Rhodes grass, 200
Rice, 56
Run-off, 274, 275, 285, 286-290, 294

S

St. Augustine grass, 232-233
Sand pine, 61
Sericea, 81
Shelter belts, 302-304, 317
Sierozems, 27, 44, 154
Silt pans, 36
*Sinapis alba*, 148
Sodium chlorate, 109
Soil, alfalfa-sick, 244
  ammonium fixation, 151-153
Soil aeration, 155
Soil compaction, 155-156
Soil conservation, 265-322
  contour farming, 281-285
  cropping systems, 277-281
  crop residue management, 290-294
  economic problems, 304-309, 317
  education, 267-273
  grassed water ways, 285-286
  infiltration, 286-290
  land classification problems, 275-277
  land use, 294-296
  pastures, 297-300
  research, 273-311, 313
  shelter belts, 302-304
  social problems, 309-311, 318
  soil losses, 294-296
  statistics, 272
  strip cropping, 300-302
  terracing, 281-285
  water losses, 288
Soil Conservation District Law, 269
Soil conservation districts, 281
Soil Conservation Service, 268, 269, 271, 272, 275, 276, 280
Soil Erosion Service, 268
Soil fumigants, 245
  diffusion, 256
Soil fumigation, 248-261
  economics, 259-261
  effectiveness, 256-259
  equipment, 253-255

  - materials, 251-253
  - methods, 253-255
  - precautions, 253
  - principles, 248-251
- Soil horizons, nomenclature, 4-5
- Soil micro-organisms, 243, 244
  - potash fixation, 153-155
- Soil nematodes, control, 244-264
- Soil parasites, 244
- Soil permeability, 276, 332
- Soil phosphorus, organic, 14, 20, 25, 26, 30
- Soil potassium, 113-164
  - clay mineral forms, 131
  - effect of aeration, 155-156
  - effect of liming, 143-149
  - exchangeable, 116-119
  - forms, 114-143
  - incalcareous soils, 150-151
  - microbial fixation, 153-155
  - movement in profile, 156-158
  - non-exchangeable, 119-131
  - primary mineral forms, 119-131
  - soluble, 115-116
- Soil survey, 277, 330
  - reconnaissance, 275
- Solonetz soils, 31, 32, 33, 34, 69
- Sorghum, 120, 151
- *Sorghum halepense*, 220
- *S. sudanense*, 233
- Soybeans, 120, 155, 287
- *Stenotaphrum secundatum*, 232
- Subsoil, 1-92
  - B horizons, 5-30
  - C and D horizons, 46-48
  - compaction, 74-83
  - concept, 4-5
  - drainage, 60, 61
  - exposed, 67-73
  - fertility problems, 72-73
  - fertilization, 83-84
  - liming, 83-84
  - management, 74-86
  - nutrient supply, 62-64
  - nutrient reserves, 84-86
  - pan layers, 31-45
  - percolation rate, 79
  - plant growth, 53-73
  - permeability, 58, 59, 60, 78
  - root penetration, 54-58
  - temperature, 48-51
  - textural range, 5-6
  - unexposed, 54-64
- Subsoiling, 77
- Subsoil layers, nature and properties, 5-30
- Substratum, 4
- Sub-surface tillage, 290, 291, 292, 293, 316
- Sudan grass, 120, 201, 230, 233-235, 286
- Sunflower, 57, 155
- Sweetclover, 26, 54, 57, 73, 77, 79, 80, 83, 120, 279

T

- Talc, 132
- Tall fescue, 202, 223, 236-237
- Taylor Grazing Act, 271
- Tennessee Valley Authority, 268, 270
- Terraces, channel type, 282
  - level, 282, 284, 285
  - vertical spacing, 283
- Terracing, 271, 274, 278, 282, 283, 284, 285, 314
- Terra Rossa soils, 15, 16
- Tillage, deep, 76-78
- Timothy, 126, 226, 237
- Tobacco, 54, 58, 118, 155, 305
- Tomatoes, 137, 148, 149, 155, 280
- Trichloroacetate, sodium (TCA), 110
- *Trifolium hybridum*, 79
- *T. pratense*, 79
- *T. repens*, 79
- Tundra soils, 8, 50
- *Tussilago farfarus*, 148

V

- Vasey grass, 200, 202, 237-239
- Vermicullite, 121, 122, 132, 133, 134, 140, 141, 142, 152

W

- Water conservation, 273
- Weathering, 128
- Wheat, 77, 126, 137
- White Dutch clover, 200, 207, 210, 213, 217, 223

Wiesenboden soils, 8, 79
Wind erosion, 66, 274, 292, 302
Wiregrass, 209

**Y**

Yellowish Brown Lateritic soils, 15

**Z**

*Zea mays*, 26
Zoysia grass, 239
*Z. japonica*, 239
*Zoysia japonica*, 239
*Z. tenuifolia*, 239

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